Development of Corrosion Resistant Storage Tanks for Solar Heated Water

RENEWABLE ENERGY BRANCH

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Energy, Mines and Resources Canada
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OTTAWA, CANADA
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PREFACE

Fundamental and practical knowledge of both corrosion and solar systems are used to investigate and develop corrosion resistant, high performance storage tanks for solar heated water.

The approach in this study consists of two parts.

A) Corrosion Control

The purpose is to study all available information, carry out certain tests and devise a means of minimizing corrosion by selecting the correct material for solar tank warranty considerations.

The scope of the work is as follows:

Literature search of existing material on hand and acquire information from other sources not on hand seeking corrosion problems and solutions.

Identify corrosion problems and develop tests.

Test each metal under consideration, i.e., 304, 304L, 316, 316L, 444, copper, steel, in worst case water.

Obtain water samples and analyze.

Set up and run water test program.

Review test results and consider ways of dealing with them.

Develop best overall method for corrosion control.

B) Engineering Design & Performance

Evaluation & design of various materials to determine their suitability for use in the construction of storage tanks and their subsequent heat transfer & retention capabilities.

The significance of the work will be long life maintenance free tanks with improved performance for solar heated water. The combined corrosion and solar system expertise will be complimentary to the solar energy development program.

This work will be of interest to equipment manufacturers and solar associations especially.

ABSTRACT

Corrosion is the primary factor that determines life expectancy and economic return on the capital investment in solar energy systems. The tank for heated solar water is the most vulnerable high-value component in terms of corrosion control in a solar energy system. Selecting the least corrosive material for tank manufacture is suggested by a series of tests and based upon an understanding of solar system types and corrosion fundamentals. In addition, the tank has to be able to effectively and efficently transfer and retain heat and thus has to be constructed to maximize the above.

I) CORROSION CONTROL

Metal samples were tested in potable water samples from locations where the greatest number of solar collectors are located. Water utility data was obtained and an aggressiveness index calculated for fifty states and seven provinces in United States and Canada.

For California and sixteen other states the choices for the least corrosive material are type 316 stainless steel with type 444 as a second alternative. For Florida the first choice is type 444 stainless steel and the alternative material is type 316 stainless steel. In all cases the tank must be passivated at the point of manufacture. Improper material selection for the tank will cause premature failure and will mean the economic benefit for solar energy will be jeopardized.

II) ENGINEERING

Tanks were designed and tested and redesigned to ensure efficient heat transfer and heat retention. Various types of heat exchangers were utilized; different types of foams & coatings were analyzed. Tanks were designed from 30 to 120 (US) gallons. Manufacturers of components for solar systems and individuals interested in solar energy development generally will be able to choose the best material for tanks based upon sound engineering principles.

large anode-to-cathode areas. The presence of chlorides is of particular concern in stainless steel tanks.

Corrosion prevention consists of material selection and passivating the tank at the place of manufacture to ensure all discrete locations such as welds, cold worked areas, scratches, etc., will develop a naturally protective film where corrosion cannot get started.

A test designed to simulate the metal in a tank using stainless steel type 304, 304L, 316, 316L, and 444 were placed in California and Florida worst case water samples. Copper and steel metal samples were placed in New York and Nevada water samples. The metal samples were weighed before and after the sixty (60) day test. The water samples were chemically analyzed for the major corrosion factors. The metal coupons were placed in the water samples and cycled relative to the normal operation of a direct active drain down type of solar system. Data from other potable water locations were analyzed and a corrosivity aggressiveness index was prepared for 50 states and seven provinces.

The results of the tests show in California, where the greatest number of tanks are sold, stainless steel type 316 is the first choice material and type 444 is second. In Florida, where the third greatest number of tanks are sold, stainless steel type 444 is the first choice and type 316 is the second choice of material. Type 304 and 304L may be the least

EXECUTIVE SUMMARY

1) Corrosion Control

Corrosion of the water tanks in solar energy systems will have a negative impact on end users. Intelligent material selection for solar tank manufcacture based on a knowledge of solar systems and corrosion fundamentals are used for the enhancement of a solar energy program. The best material or conversely the least likely material to corrode is suggested from tests undertaken where the greatest number of solar collectors are located for worst case potable water and from 387 utilities in the United States and Canada.

The corrosion of metals takes place in an electrochemical cell involving an anode and a cathode that are interconnected and in contact with a common electrolyte. The anode in this cell corrodes at a rate dependent on the amount of current circulating. The current may be driven by the cell itself due to the anode and cathode being of different metals. The current can also be driven externally by concentration differences in the solar heated water in contact with the inner surface of the tank. A corrosion cell need not result in severe damage, the activity being limited by an undamaged natural protective film, high electrolyte resistivity, low anode - cathode potentials and

expensive material in 26 states and five provinces. In all other locations type 304 is rejected if the chloride level is greater than 25 ppm. maximum. Type 316 is the least costly material in 16 states and one province. Copper and steel are rejected because they will not achieve the desired maintenance-free life required in solar energy systems.

The highlight of the tests is that a choice of type 316, and 444 stainless steel will be the least corrosive materials when considering all corrosion factors. This choice is true for the California and Florida locations where the greatest number of solar collectors are located. It is also true for locations such as New York and Nevada.

Although type 444 stainless steel is at least double the cost of type 304 it has a successful operating history and is standard for solar collectors in Japan. The tests confirm that type 444 protective oxide film was always passive. Conversely, type 316 was always active, and type 316L was both active and passive depending on the test cycle.

The solar water storage tank corrosion control study shows important material selection choices in the development of corrosion resistant storage tanks for solar heated water. A significant advance is made in using information about the

corrosiveness of water where 70% of existing tanks are located and where at least one-half of new tank sales in both United States and Canada can benefit from a greatly improved stainless steel material selection process.

Further research under the solar energy development program would be complimentary to enhancing the economic return on capital investment for solar heating systems. Since corrosion is the primary factor in determining the life expectancy and since the only component which cannot be made from non-corrodable material is the tank, it is justifiable to obtain more corrosion factor information by additional funding. The increased effectiveness and increased use of future solar systems is at stake here.

2) ENGINEERING PERFORMANCE

The performance of a solar system depends to a large extent on the ability of a storage medium (tank) to collect and retain heat. In many specific systems the tank is regarded as a least cost add on.

The objective of this part of this study is to determine which materials are best suited for manufacturing & to develop a line of tanks which are cost effective yet provide excellent performance. The studies on corrosion also played a part in material selection.

In total 13 tanks were developed ranging from 30 to 120 US gallons. Design was based on an analysis of 22 different types of tanks, currently being marketed, and pertinent engineering data.

Materials analyzed include a range of stainless steel, copper , copper reinforced with fiberglass, bronze and mild steel coated with various coatings. Analysis was completed of a variety of foams and jackets for these tanks.

The tanks were tested by linking them up to a 200,000 BTU boiler. They were tested for heat build up, stand-by loss and instantaneous heat draw, and for pressure.

Tank performance varied from 116 to 206 US gallons of water at 140ºF (30 to 120 gallon) for the first hour and 43 to 77 US gallons for a 10 minutes draw. Heat retention varied from 2.6 to 1.2 % loss per hour (30 to !20 gallon).

In summary, it showed that 16 gauge Stainless Steel was the best and most economic material to use. The type of Stainless used depended on corrosion considerations. Rigid Iso foam 2A and Polystern provided the most cost effective foam insulation and jacket materials.

This section of the study shows consistently that important considerations must be given to the "tank" component of the solar system. The study has high-lighted what factors should be considered in tank design. Further research could be completed in this area by running tanks from approved systems and comparing them to the results presented here.

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INTRODUCTION

There are two major technical objectives of this study.

1) To determine the most appropriate types of materials for the construction of solar storage tanks for use under various water conditions, considering cost-effectiveness and longevity (corrosion control).

2) To determine the most appropriate design and materials for insulation and heat exchange coils for use under various water conditions.

To a large extent the two objectives are self-supporting and are thus presented as seperate components in this report.

STATE OF THE ART

At this time, solar suppliers and dealers are using basically two types of tanks:

- Mild steel glass-lined tanks; and
- 304 Stainless steel tanks.

Mild Steel Tanks are made from mild steel and are glass-lined. Some tanks have anodes which are designed to inhibit corrosion. These tanks are wrapped with bat-type insulation and jacketted. They usually have warranties from two to five years. Leaking, due to corrosion or cracking of the glass lining, is common and the average life of a tank is a little over five years. In addition their heat transfer & retention is questionable.

Stainless Steel Tanks. Extensive use is made of 304 stainless steel with a normal thickness of 1/16" or less. (304 is the least expensive grade of 300 series stainless steel). Many of these tanks are not chemically treated (passivated) after welding. Tanks may rust through within one year due to poor metal preparation, welding and lack of chemical treating. Different types of insuluation are utilized. Warranty periods are from two to ten years.

CORROSION CONTROL

Introduction

This investigation of solar water tank corrosion control is intended to act as a guide for achieving a long life expectancy in residential or commerical types of solar systems. The metal selected for tank manufacture is important if the economic return on investment is to be fully realized. Due to the diversity of solar hot water system types, many different metallic components and the wide range of chemical and physical makeup of potable water throughout North America, it is not feasible to identify specific measures for all situations. Instead, the approach has been taken of outlining the principles generally involved with corrosion and its prevention and then examining their application in a worst case solar water heating system.

Although there is a considerable body of knowledge about the causes and prevention of corrosion, most of this knowledge results from industries where the aggressiveness is more severe and some of the information is not aplicable.

Information for the investigation was selected from four sources. In the first instance, information was obtained by a review of published literature in the form of technical papers, reports and texts. Information about the metals under study was obtained from manufacturers' technical data. The aggressiveness of the potable water electrolyte came from data supplied by the American Water Works

Association. Finally, water samples were collected and experiments were performed to help in determining the practical application in situations where existing knowledge appeared inadequate.

Objectives

The objectives of the work described in this investigation are:

1. To suggest the best material for solar heated water tank manufacture for worst case locations to achieve a maintenance free fifteen-year life minimum.
2. To provide fundamental and practical knowledge of both solar system types and corrosion fundamentals.

Method

The work began by a lengthly review of published literature in the form of technical papers, reports and texts. The applicable knowledge gained from this can be found in Appendix "A" solar hot water system types and in Appendix "B" corrosion fundamentals, theory, mechanics, kinetics, and corrosion prevention.

Metallic material samples were obtained for consideration, namely, stainless steel type 304, 304L, 316, 316L, 444, copper and mild steel. These materials are considered good for hot water applications.

Potable water samples were obtained from locations where the

greatest number of solar collectors are located. Chemical and physical analysis of the water samples were used to determine worst case electrolyte aggressiveness.

The certified mill test report for each metal sample is located in Appendix "C".

Each metal sample was 127 mm (5") long by 19 mm (0.75") wide by 1.5876 mm (0.0625") thick and was u-bent to A.S.T.M. G30 specifications to represent a stressed specimen similar to a rolled tank wall cylinder. Two samples of each metal were then welded together along the 127 mm (5") long edge using the following welding filler rod and the TIG welding process:

Metal Sample	Filler Rod	TIG Process
304	308	"
304L	308L	"
316	316	"
316L	316L	"
444	316L	"
Copper	Silicon & Bronze	"
Steel	H/T Steel	"

The stainless steel corrosion coupons were then passivated in a 25% nitric acid and 75% water solution at 49° Celsius (120° F) for 20 minutes. This is the standard passivation procedure by A & R Metal Industries Ltd.

The weight of each corrosion coupon was measured prior to the test in different potable water (details on these weights can be found in Appendix "C") and is reported as follows:

Corrosion Coupon	Identification	Initial Weight in Grams
304	1 & 2	54.4161
304L	1 & 2	51.5412
316	1 & 2	50.7760
316L	1 & 2	50.0953
444	1 & 2	60.1618
304	3 & 4	55.5499
304L	3 & 4	51.7680
316	3 & 4	51.4945
316L	3 & 4	50.6051
444	3 & 4	60.1198
Copper	3	60.5342
Steel	1 & 2	51.2652
Copper	1	60.2550
Copper	2	58.3017
Steel	3 & 4	51.6858
Steel	5 & 6	51.0413

Water samples were obtained using several sources including The California Solar Association records of where solar collectors are sold. This information can be found in Appendix "C" and shows the following:

California	52%
New York	10%
Florida	8%

Water samples were obtained from the following locations:

California

New York

Florida

Nevada

Vancouver

Texas

Georgia

Windsor

The water samples were analysed and ranked with regard to corrossiveness factors which are found in Appendix "C" and reported as follows:

Location	Chlor-ides	pH	Resis-tivity	Aggressiveness	Alka-linity	Hard-ness
Californa	49	8	1,205	11.44 Moderate	120	49
Nevada	49	7.2 Optimum	1,105	11.76 Moderate	133	49
Florida	42	6.6 Corrosive	5,263	10.54 Moderate	79	42
New York	40	6.5 Corrosive	2,083	10.74 Moderate	98	40
Vancouver	--	5.9	28,571	7.7 High	5	0.9
Texas	--	-	1,739	11.73 Moderate	201	-
Georgia	--	6.5 Corrosive	6,897	10.05 Moderate	65	-
Windsor	--	6.5 Corrosive	3,448	10.56 Moderate	87	-

The reasons for ranking in this order can be found in Appendix "A" corrosion prevention, environmental control.

The water samples selected for corrosion coupon testing were:

California

Florida

New York

Nevada

The metal samples were stressed using a stainless steel bolt in the hole provided. Each bolt was electrically insolated from the corrosion coupon. The coupons were suspended in a beaker containing the previously selected water samples as follows:

Water Sample Location	Metal Sample Type	Metal Identity Number
California	304	1 & 2
California	304L	1 & 2
California	316	1 & 2
California	316L	1 & 2
California	444	1 & 2
Florida	304	3 & 4
Florida	304L	3 & 4
Florida	316	3 & 4
Florida	316L	3 & 4
Florida	444	3 & 4

Water Sample Location	Metal Sample Type	Metal Identity Number
New York	Copper	1
New York	Copper	2
New York	Steel	1 & 2
Nevada	Copper	3
Nevada	Steel	3 & 4
Nevada	Steel	5 & 6

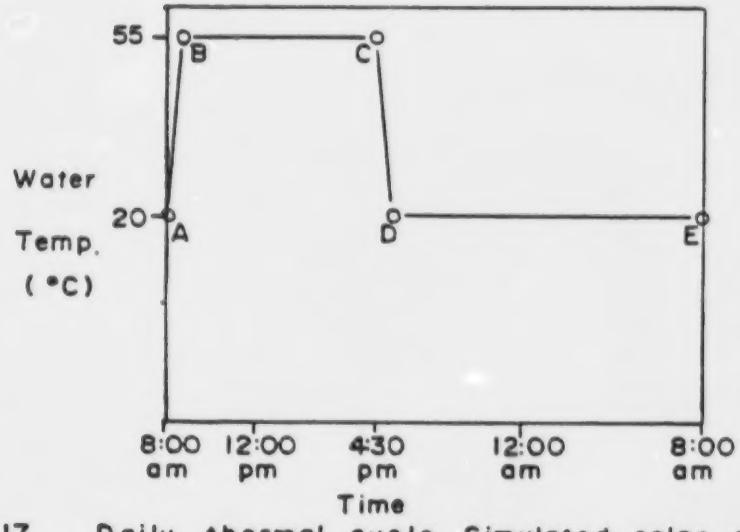


Figure 17. Daily thermal cycle. Simulated solar service test.
Operating conditions:
A = Heating of water begins.
B = Daily maximum operating temperature obtained
C = Heating off at 4:30 pm.
D = Water aerated.
E = Daily thermal cycle repeated.

The daily thermal cycle was as shown in Figure 17. Twelve of the sixteen test cells were placed on a regulated temperature

plate. The remaining four stayed at room temperature. The daily thermal cycle - simulated solar service test commenced heating at 8:00 A.M. through 4:30 P.M., then was allowed to cool down to room temperature for the remaining 15.5 hours. Once each day the water in each test cell was aerated by allowing the solution to free fall into another beaker. Once each day the potential was measured with reference to a saturated calomel reference electrode.

The corrosion coupons were visually examined for any corrosion damage and at the end of 60 days the test was terminated and each coupon was cleaned in accordance with A.S.T.M. G1-79 standard specification and reweighed.

Results

Corrosion of metal is an oxidation process whereby positively charged ions leave the metal and enter the electrolyte. Different metals have different tendencies to corrode, the most active being those with the most negative electrical potential when in an aqueous environment.

All corrosion cells have the following:

- An anode (corrodes).
- A cathode (does not corrode).
- An electrolyte (potable water stored in the tank).
- External electrical path between the anode and cathode (solar tank).

The weight loss from the anode is related to the magnitude of this cell current. A small anode area connected to a large cathode area will result in more damage than if the reverse area relationship were true.

Corrosion cells are driven either by galvanic action internally, i.e., a steel tank in a copper piping system or by potable water concentration differences external to the particular metal surface in contact with the electrolyte.

i.e., General Mineral Oxygen

Carbon Dioxide

	Chlorides
	pH
	Alkalinity
	Hardness
	Resistivity/Conductivity
General Physical	Temperature
	Flow (Turbidity)
	Aggressiveness Index
	Langelier Saturation Index
	Ryznar Stability Index

The electrical potential of each corrosion coupon was measured with a high resistance D.C. voltmeter and a saturated calomel reference electrode. The purpose is to determine the corrosion tendency of the metals included in the test.

The practical galvanic series, found in Appendix A, Corrosion Fundamentals, Table 3, was expanded to include the stainless steels tested. Oxide films which form naturally can provide substantial protection against corrosion attack by the aqueous environment. Different types of stainless steel will form a film or not form a film depending on the effect of oxygen and oxidizing agents on the corrosion cell. It is said that a stainless steel is passive if its measured potential resembles that of a more noble metal such as gold. Conversely, it is said that a stainless steel is active if its measured potential

resembles that of a more active metal such as magnesium. The anticipated corrosion cell activity for the metals tested in the aqueous environment where the most solar heated water tanks are sold are shown in the table as follows:

Metal	Corrosion Coupon Potential Measured In Volts Saturated Calomel SCE	Copper Copper Sulphate $CuCuSO_4$	Corrosion Tendency
Magnesium	-1.508	-1.75	
Steel	-0.694	0.936	Greatest
316L Active Fld.	0.251	0.493	
304 Active Fld.	0.167	0.409	
444 Passive Cal.	0.150	0.392	
316 Active Cal.	0.122	0.364	
316 Active Fld.	0.100	0.342	
304L Active Fld.	0.085	0.327	
444 Passive Fld.	0.071	0.313	
Copper N.Y.	0.068	0.310	
304L Passive Cal.	0.046	0.288	
Copper N.Y., Nev.	0.032	0.274	
316L Passive Cal.	0.028	0.270	
304 Active Cal.	0.026	0.268	Least
Carbon	+0.058	+0.300	
Gold	+1.048	+1.364	

Practical galvanic series revised to include metals tested showing relative tendency to corrode.

The electrical potential of each corrosion coupon measured with a high resistance D.C. voltmeter and a saturated calomel reference electrode (SCE) are shown in the following table:

Metal	Identification Number	Potable Water Location	Electrical Potential, -Volts SCE
Stainless Steels			
Type 304 (Active)		California	0.026
316 (Active)		California	0.122
304 (Active)		Florida	0.167
304L (Active)		Florida	0.085
316L (Active)		Florida	0.215
316 (Active)		Florida	0.100
316L (Passive)		California	0.028
444 (Passive)		California	0.150
444 (Passive)		Florida	0.071
304L (Passive)		California	0.046
Copper			
	2	New York	0.068
	1	New York	0.032
	3	Nevada	0.032
Steel			
	5, 6	Nevada	0.825
	3, 4	Nevada	0.696
	1, 2	New York	0.691

Table showing electrical potential of each corrosion coupon with reference to saturated calomel electrode.

The weight loss for each corrosion coupon, hence the magnitude of current driving the corrosion cell mechanism during the test, is shown in the table as follows:

Corrosion Coupon Identification		Electrolyte	Initial Weight In Grams	Final Weight In Grams	Weight Loss In Grams After 60 Day Test
Stainless Steels					
Type 304	1, 2	California	54.4161	54.4069	0.0092
304L	1, 2	California	51.5412	51.5247	0.0165
316	1, 2	California	50.7760	50.7756	0.0004
316L	1, 2	California	50.0953	50.0697	0.0256
444	1, 2	California	60.1618	60.1575	0.0043
304	3, 4	Florida	55.5499	55.5415	0.0084
304L	3, 4	Florida	51.7680	51.7619	0.0061
316	3, 4	Florida	51.4945	51.4903	0.0042
316L	3, 4	Florida	50.6051	50.5890	0.0161
444	3, 4	Florida	60.1198	60.1164	0.0034
Copper	3	Nevada	60.5342	60.4716	0.0626
Copper	1	New York	60.2550	60.2118	0.0432
Copper	2	New York	58.3017	58.1482	0.1535
Steel	1, 2	New York	51.2652	49.6740	1.5912
Steel	3, 4	Nevada	51.6858	50.4008	1.2850
Steel	5, 6	Nevada	51.0413	50.4243	0.6170

Table showing weight loss for corrosion coupons tested.

The preceding results based on sixteen metals using six different

corrosion factors in four worst case potable waters show the following:

Stainless Steels		Copper	Steel
California	Florida	New York	Nevada
316	444	Nevada	New York
444	316	New York	New York
304	304L		
304L	304		
316L	316L		

Comment: - Stainless steel type 304, 304L and 316L are eliminated as a suitable material on the basis of this test.

- Copper and steel are eliminated due to excessive corrosion rates on the basis of this test.

A great deal of emphasis in the literature is placed on potable water being well conditioned or over saturated with calcium carbonate (lime) which improves the tendency for laying down a protective film on the internal surface of the tank.

On the basis of using one corrosion factor, namely, the aggressiveness index the following information has been calculated from a survey of 387 utilities serving 109 million people in Canada and the United States by the American Waterworks Association in 1984.

- Sixty per cent (60%) of 387 utilities have moderately to highly aggressive water.

- Eleven per cent (11%) have highly aggressive water.
- Forty-nine percent (49%) have moderately aggressive water.
- Forty percent (40%) have non aggressive water.

CORROSIVITY AGGRESSIVENESS INDEX

FROM FINISHED POTABLE WATER SOURCES

IN UNITED STATES AND CANADA

This index is a guide for anticipated corrosion of solar heated water tanks using a combination of three factors, namely, the pH, alkalinity and hardness, calculated from the following formulae:

Highly Aggressive: pH log (AH) less than or equal to 10.0

Moderately Aggressive: pH log (AH) equals 10.0 to 11.9

Non Aggressive: pH log (AH) more than or equal to 12.0

	33.3% Per Cent of States Highly Aggressive		56% Per Cent of States Moderately Aggressive		11% Per Cent of States Non Aggressive	
	United States					
	Oregon	7.86	Arkansas	10.02	Kansas	12.00
*10% tank	New York	8.14	Tennessee	10.06	Idaho	12.02
	Maine	8.25	Texas	10.10	Oklahoma	12.12
	Minnesota	8.30	Maryland	10.24	South Dakota	12.20
	Rhode Island	8.41	Colorado	10.26	North Dakota	13.15
	Connecticut	8.46	Pennsylvania	10.30		
	North Carolina	8.75	Georgia	10.31	* Montana Not Reported	
	New Hampshire	8.84	Ohio	10.47		
	South Carolina	8.87	New Mexico	10.51		
	Washington	8.88	Wisconsin	10.54		
	Wyoming	8.95	Alaska	10.60		
	West Virginia	8.96	Missouri	10.80		
	Massachusetts	8.98	Hawaii	10.82		
*52% tank	California	9.31	Delaware	10.94		
* 9% tank	New Jersey	9.58	Illinois	11.01		
	Nevada	9.93	Alabama	11.05		
	Virginia	9.97	Utah	11.26		
	Indiana	10.00	Michigan	11.36		
			Louisianna	11.44		
			Vermont	11.44		
			Iowa	11.51		
			Dist. of Columbia	11.68		
			Mississippi	11.74		
		*4% tank	Arizona	11.77		
		*8% tank	Florida	11.80		
			Kentucky	11.80		
			Nebraska	11.84		
	Canada					
	Newfoundland	8.10	British Columbia	10.38	Alberta	12.21
			Ontario	10.86		
			Manitoba	11.41	* Quebec, Nova Scotia, P.E.I. Not Reported	
			New Brunswick	11.57		
			Saskatchewan	11.64		

References:- A.W.W.A. 1984 Water Utility Operating Data.
- Millette J.R. and others. Aggressive Water: Assessing The Extent of The Problem, A.W.W.A. Journal P. 262 - 266, May 1980.

Note: Locations are ranked by order of worst case. i.e., Medford, Oregon is 7.86, therefore, the whole state is a 33.3% risk that a tank installed there will corrode.
i.e., Tampa, Florida is 11.80, therefore, there is a 56% risk that an installed tank will corrode.

Summary

The results of the test show that considering all corrosion factors the choice of stainless steel material for solar water storage tank manufacture by location is as follows:

California — Type 316, 444

Comment: Types 304 and 304L are rejected due to chloride level being in excess of 25 ppm. maximum.

Florida — Type 444, 316

Comment: Opposite to California.

New York — Type 316, 444

Comment: Same as for California.

Nevada — Type 316, 444

Comment: Same as for California.

16 other states and one province — Type 316 or better

Comment: Type 304L can be used if chloride level is 25 ppm. maximum.

26 other states and five provinces — Type 304 or better

Comment: Type 304L can be used if chloride level is 25 ppm. maximum.

This information was developed from the following table:

Choice	Location	Per Cent Error	Corrison Factors: Potential In Volts SCE	Chlorides mg/L	pH	Resistivity Ohms Cm.	Aggressiveness (pH, alkalinity, hardness)	Oxide Film A-Active P-Passive	Weight Loss Milligrams	Material	Cost Factor
1	California	0	0.100	49	8	1,205	11.44	A	4	316	151
2		0	0.150	49	8	1,205	11.44	P	43	444	202
1	Florida	5	0.071	42	6.6	5,263	10.54	P	34	444	202
2			0.100	42	6.6	5,263	10.54	A	42	316	151
1	New York	10		40	6.5	2,083	10.74			316	151
2		10		40	6.5	2,083	10.74			444	202
1	Nevada	10		49	7.2	1,105	11.76			316	151
2		10		49	7.2	1,105	11.76			444	202
16 other states and one province		50									

Reference to Corrosivity Aggressiveness Index 33.3% Highly Aggressive Use — 316 or better

- Chloride level is determining factor, if chlorides are 25 use 304L or better

if chlorides are 100 use 316L or better

26 other states and five provinces	50	

Reference to Corrosivity Aggressiveness Index 56% Moderately Aggressive Use — 304 or better

- Chloride level is determining factor, if chlorides are 25 use 304L minimum

if chlorides are 100 use 316L minimum

Table showing minimum acceptable stainless steel material selection based on all corrosion factors and worst case location showing per cent error.

DISCUSSION

Galvanic

It has been mentioned several times throughout this report that galvanically driven corrosion cells are often more severe than the aggressiveness of the water supply. Even though the tank may be manufactured from metal with the least tendency to corrode, the tank may be installed where a greater tendency to corrode is prevalent due to galvanic action.

Concentration Differences in the Water Supply

The solar system type with the most corrosion activity is the direct active drain down. The worst case situation would be to have this highly oxygenated system with a type 316L stainless steel tank in California having 49 mg./L cholorides, closely followed by Nevada, Florida and New York. If one were to pursue the information contained in this report on California, it can be shown that 52% of solar collectors were sold there in 1981 and according to American Waterworks Association 33.3% of the tanks sold in that state will `contain highly aggressive water. The potable water is not capable of forming a protective film.

A review of the certificate of analysis found in Appendix "B" for the eight water samples collected and corrosive aggressiveness index found in the results section of the report shows the almost endless variation in the water supply. Furthermore, a review of the complete chemical analysis during September 1986 shows the variation from five water sources in one city in California, namely, San Diego. This information can be found in Appendix "C" of this report.

It should be pointed out that the chloride levels range from 57.2 to 88.8 mg/L in San Diego and that type 304L stainless steel is not recommended for water having 25 ppm Cl^- maximum to avoid stress corrosion cracking.

Corrosion Pitting

The practical evidence is that unpassivated type 304 stainless steel is subject to rapid corrosion pitting. The various types of stainless steels included in the test were all passivated as a corrosion prevention measure and they exhibited development of a protective film, which ranged from easily destroyed, to difficult to destroy, in the following order:

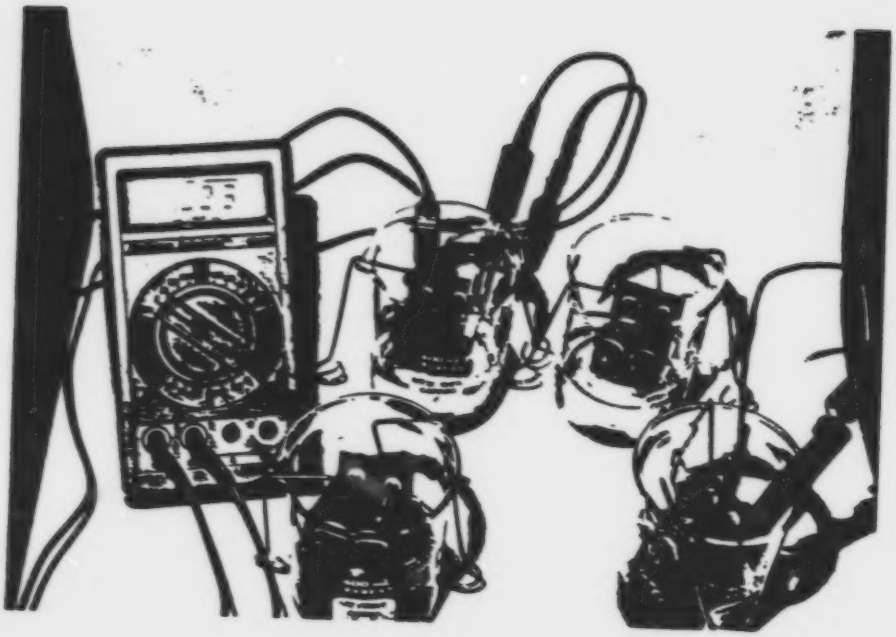
Potable Water Location	Stainless Steel Corrosion Coupon	Active/Passive Film	Protective Film Destruction
California	304	Always Active	Easily Destroyed
California	316	Always Active	Easily Destroyed
California	316L	Active/Passive	Easily Destroyed

Potable Water Location	Stainless Steel Corrosion Coupon	Active/Passive Film	Protective Film Destruction
Florida	304L	Always Active	Easily Destroyed
New York	Copper	Passive	Easily Destroyed
Note: Steel does not develop protective film.			
Florida	304	Active/Passive	Not Easily Destroyed
Florida	316L	Active/Passive	Not Easily Destroyed
Florida	316	Always Active	Not Easily Destroyed
California	304L	Always Passive	Difficult to Destroy
California	444	Always Passive	Difficult to Destroy
Florida	444	Always Passive	Difficult to Destroy

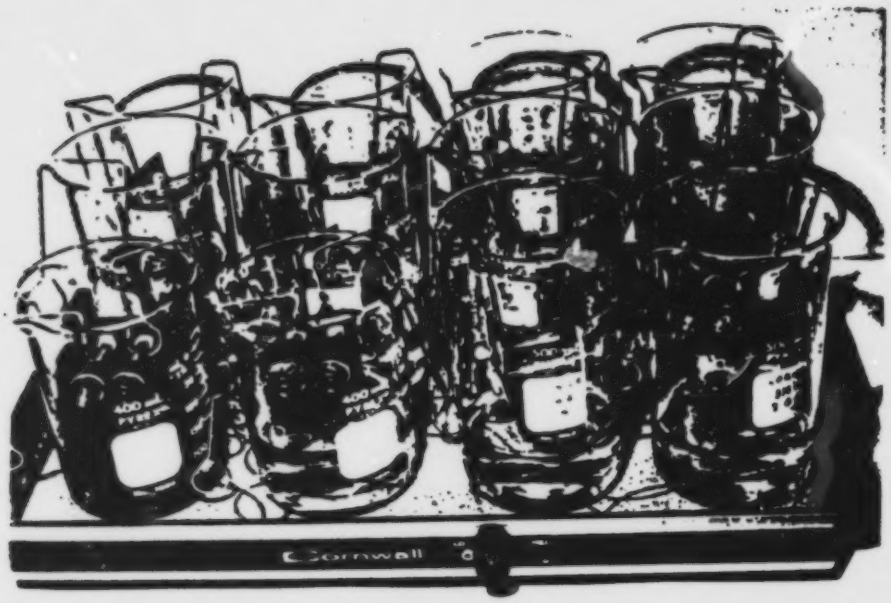
The purpose of showing this information is to demonstrate that passivating stainless steel tanks is considered the first line of defence in minimizing corrosion pitting. It also shows why type 444 stainless steel is in standard use for solar collector service in Japan.

Although copper has a low negative value in terms of Gibb's free energy indicating the least tendency to corrode, it develops a fine grained protective film which is easily disturbed. When the film is disturbed a small anodic site starts corrosion cell activity and a pit is formed leading to premature tank failure.

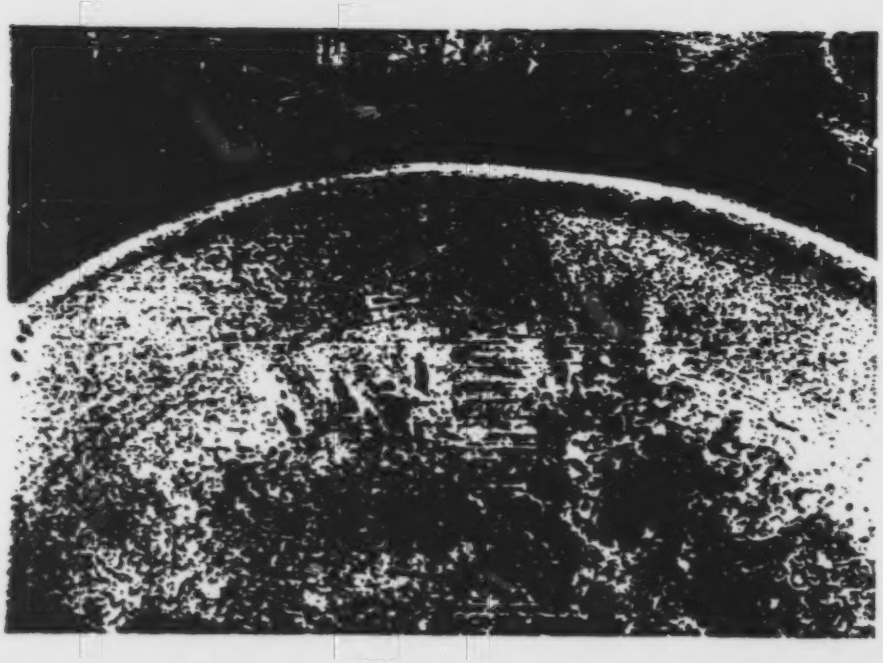
Photographs



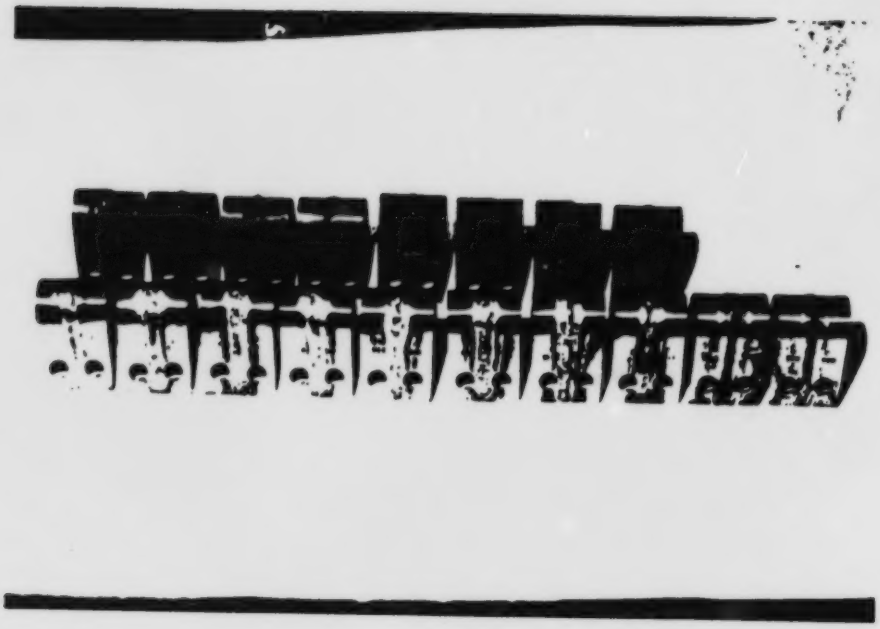
Measuring the potential of copper to silver chloride reference electrode



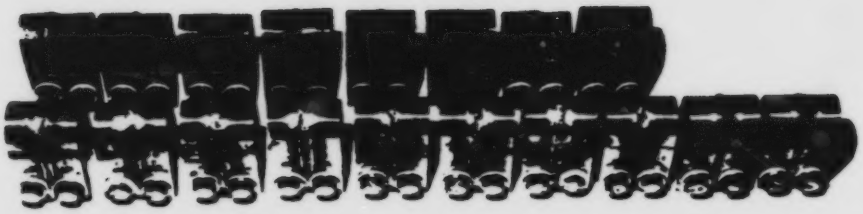
Corrosion coupon test setup



Corrosion pitting of an unpassivated type 304 stainless steel tank as described in Figure 16, Appendix B

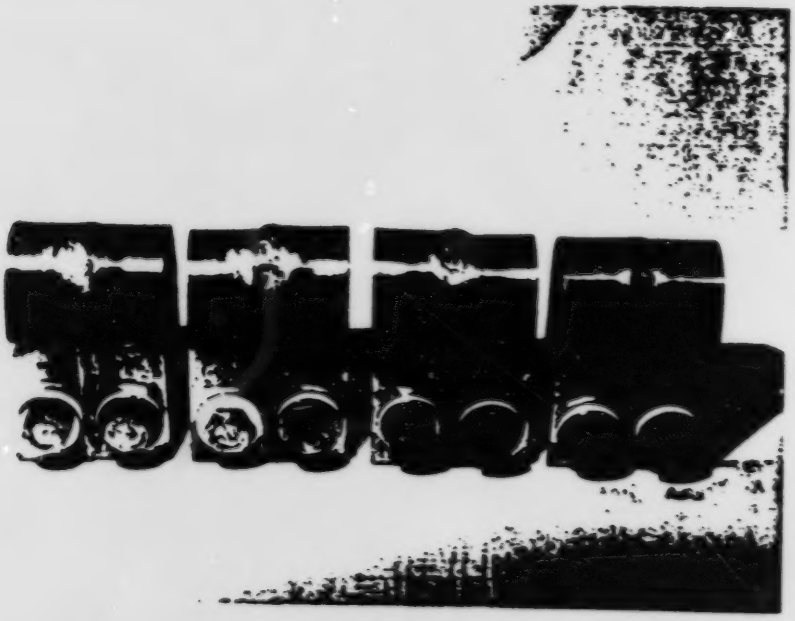


Corrosion coupons before tests



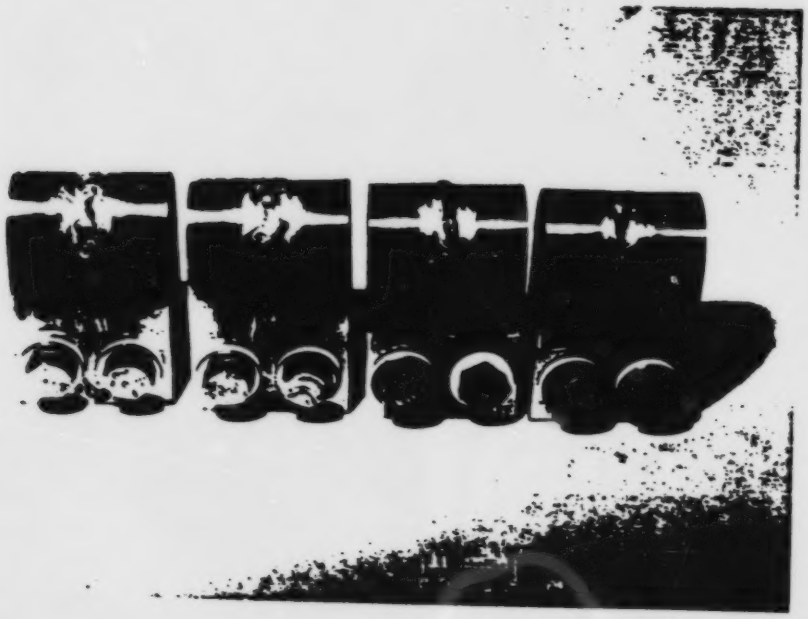
Corrosion coupons after tests

Type 304 stainless steel coupons before test



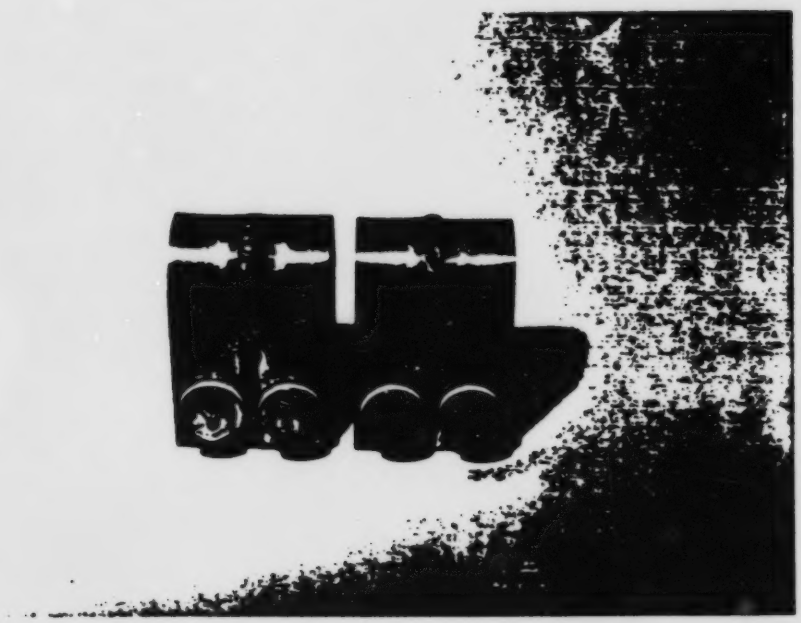
Type 304 stainless steel coupons after test

Type 316 stainless steel coupons before test



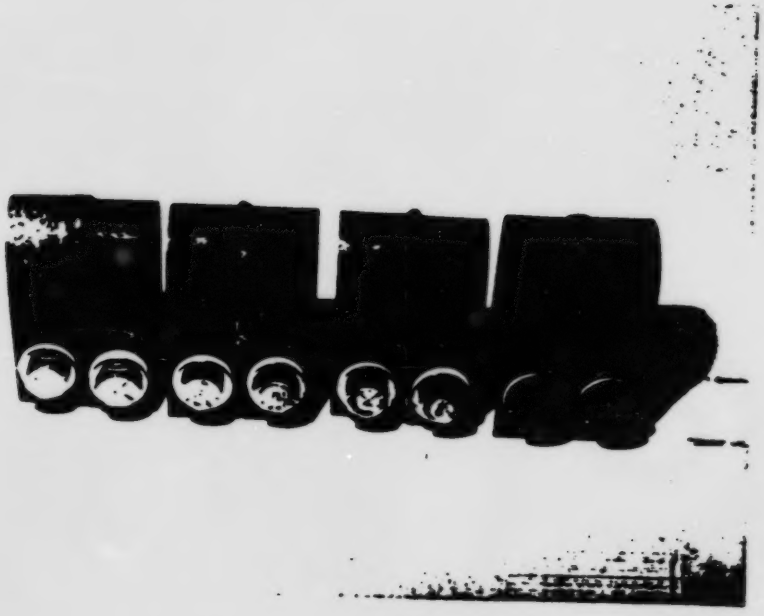
Type 316 stainless steel after test

Type 444 stainless steel coupons before test

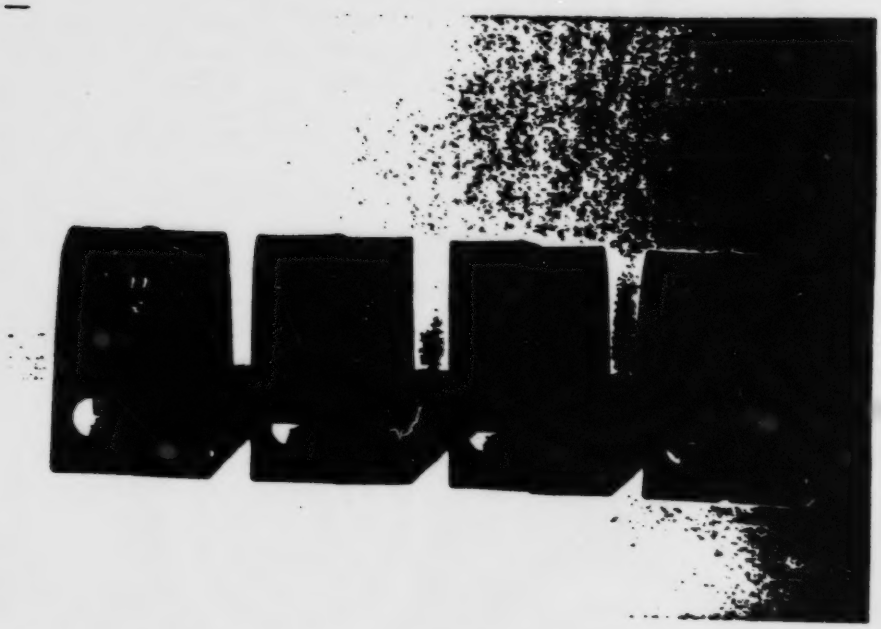


Type 444 stainless steel coupons after test

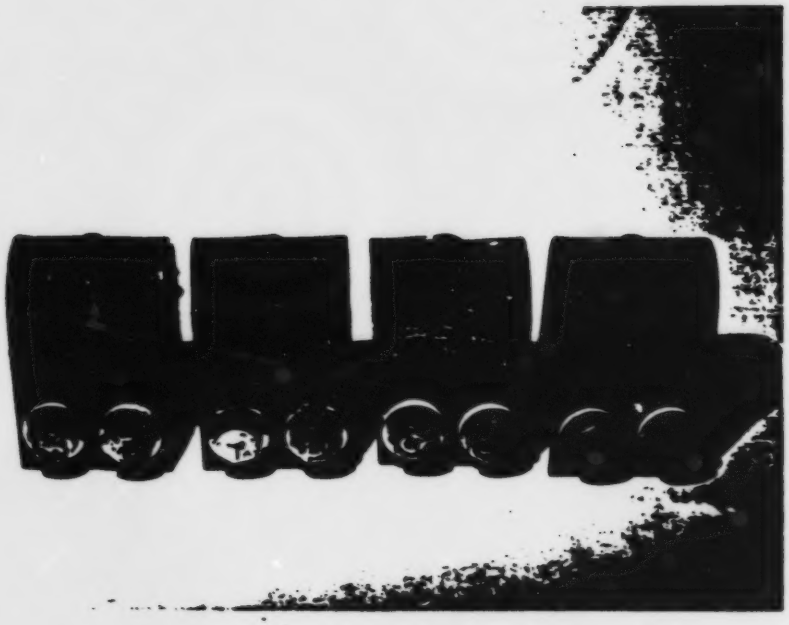
Copper coupons before test



Copper coupons after test



Steel coupons before test



Steel coupons after test

Conclusions

Firstly, the solar water storage tank corrosion control study shows that provided each tank is adequatedly passivated, type 316 and 444 are the best materials for California. Type 444 and 316 are the best materials for Florida, New York and Nevada locations. Type 304 and 304L are not recommended for use in the above named four states because the chloride levels are too high. There is fifty percent (50%) chance that type 316 or better will be sufficient in sixteen (16) other states having highly aggressive water. There is also a fifty percent (50%) chance that type 304 or better would be sufficient in twenty-six (26) other states having moderately aggressive water.

Secondly, the solar water storage tank corrosion control study has also provided a significant advance in using information about the corrosiveness of the potable water in states where seventy percent (70%) of the tanks are located. It also provides a basis from which at least half of the remaining tank locations can receive the benefit of a better stainless steel material selection process. If the chloride level could be determined the chance of error could be improved. Similarly, for the remaining 41 states and 6 provinces, for which information is available, the chance of error could be improved if the chloride level was known. Further work beyond the financial limitations of this study is recommended.

Thirdly, this study shows that the combined expertise in corrosion control and solar heat when based on sound engineering principles can lead to significant advances in material selection which is beneficial to the economic return on capital investment for solar heating systems.

Recommendations:

1. Type 316 stainless steel is the most corrosion resistant metal for solar water tanks in California. It is a medium priced material.
2. Type 444 stainless steel is the most corrosion resistant metal for solar water tanks in Florida. It is also the most expensive material.
3. Consult the corrosion aggressiveness index as a guide for selecting the least corrosive material for solar water tanks in other locations in North America.
4. Further research under the Solar Energy Development Program would be complimentary to enhancing the economic return on capital investment for solar heating systems. Since corrosion is the primary factor in determining the life expectancy and since the only component which cannot be made from non-corrodable material is the tank, it is justifiable to obtain more corrosion factor information by additional funding. The increased effectiveness and increased use of future solar systems is at stake here.

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2)

DESIGN & PERFORMANCE TESTING

i) Introduction

Most solar intallation utilize an "existing" tank. Alternatively they utilize a tank designed for a particular system or sytems, and have cost as their prime consideration. The tank is regarded as storage. We believe that little consideration is given to performance. Performance is defined as the ability to transfer heat (if a transfer medium is utilized) and to retain heat. We view the efficiency of the tank (i.e. to transfer, if applicable, and retain heat) as an integral part of the overall system efficiency.

Contact with Canadian and United States solar companies indicated the above. Any consideration of performance increase, if it resulted in even minimal cost increases, were met with strong resistance.

ii) Objectives

The objectives of this part of the study was to achieve an analysis of performance/cost considerations of the solar storage tank. This was done by examining types of materials, foams, methods and means of manufacture etc., overall design, and then relating these to cost. The economic performance of tanks could then be evaluated. This cost/benefit analysis can then be utilized in the overall economic performance of solar systems.

METHOD: SUMMARY

Hot water tanks, with heat exchangers, were designed with a number of criteria addressed in the design:

-Cost

-Performance-pressure

-Performance-heat retention

-Heat gain build-up and continuous draw.

These tanks were designed taking into account the above as well as corrosion considerations.

A number of materials were examined; these included stainless steel (304, 304L, 316, 316L, 444), copper, copper wrapped with fiberglass, and mild steel coated tanks.

Once preliminary design had been developed, prototype tanks were developed ranging from 30 to 120 gallons (U.S.). Consideration was given to a variety of types of insulation and jacketing. These considerations were based on cost, heat retention performance, manufacturing methods, aesthetics and rigidity.

These tanks were then tested by using 200 MBTU Boiler, pumps and a Campbell Scientific CR21 data logger. The results were then analyzed and tabulated by Ken Cooper under a subcontract.

i) ENGINEERING AND DESIGN:

A complete analysis was done on some 22 different types of hot water tanks currently available. These involved collecting technical and pricing data and then analyzing this data for performance, etc. The types of tanks ranged from the domestic hot water tank (electic or gas), which is made with glass-lined mild steel with fiberglass-type insulation, through to various types of "high performance" tanks.

A line of tanks was then designed taking into account the above as well as manufacturing and marketing considerations.

The line of tanks designed were:

30 U.S. gallon
40 " "
60 " "
70 " "
80 " "
100 " "
120 " "

All these were designed with a coil and 40 to 120 gallon tanks also with a double coil (total 13 tanks). These designs took into account such consideration as door sizes, height and width calculations, etc. Head designs were based on pressure calculations .

Once the basic designs were established consideration was given to the type of materials from which these tanks were to be constructed. The following materials were analyzed and considered: stainless steel, mild steel (coated), copper, bronze, and reinforced copper.

A means of ensuring that as much heat as possible was retained within the tank was then addressed. A number of types of foam were tested. These are detailed in the result section. The R value of each foam, any considerations of heat loss due to voids on that foam, were then analyzed. In addition, manufacturing ease and considerations were analyzed.

STAINLESS STEEL TANKS

TANK DESIGN & SPECIFICATIONS

Attached are bills of material for all Solar storage tanks. (Appendix D). These tanks have been developed using 304 (16 gauge). Bill of material for tanks with 2 heat exchangers would require two extra nipples and an additional coil.

Manufacturing specifications and estimated times are attached.

COST SUMMARY

Total material cost based on the listed bill of material are:

AM 30-1	72		
AM 40-1	98	-2	119
AM 60-1	125	-2	152
AM 70-1	119	-2	146
AM 80-1	140	-2	179
AM100-1	163	-2	214
AM120-1	191	-2	248

COPPER TANKS

a) Our analysis consisted of calculations of material thickness and requirements as compared with Stainless Steel. We analyzed a 40 gallon thermosphan tank A & R is currrently supplying.

The all copper tank would cost	$366
A fiberglass wrapped copper tank would cost	$250
A bronze tank would cost	$167
This compares with 16ga Stainless Steel tank	$128

While both copper & fiberglass wrapped copper tanks are more expensive that the existing 16ga 304 SS tank there may be corrosion considerations that fully warrant their use under certain situations.

b) (See appendix E.)

c) The fiberglass which would be applied to the light gauge copper tank would be:

1 layer of M751 chopped strand mat (450 g/m2) and extending between the end cap weld lines.

4 layers of hoop winding with 432-2200 tex filament winding roving and extending between the end cap weld lines.

1 layer of M751 chopped strand mat (450 g/m2) extending between the end cap knuckle radii.

2 layers of 432-2200 tex filament winding roving, one at +32º, the other at -32º to the axis of the tank and extending over each end cap.

The geometry of these last two winding layers was selected so the strands follow a great circle over the end caps to prevent any tendency for the strands to slide

COPPER TANKS - PRICES

SUMMARY

ALL COPPER TANK
15 5/8 X 51 3/4 DYNASTY

Copper @ 1.85/lb mill run X 116 lb = 214.60				214.60
duty not in price				
Fittings	1	ø X 2	1.84	3.68
	3/4	ø X 3 X	1.05	3.15
	Filler rod item			5.00
Mark-up @ 1.15 X 226.43 = 260.39				33.96
Labour - same as for SS + 15 min. for handling due to weight				60.00
			TOTAL	320.00

WRAPPED COPPER TANK

48 X 48 X 22ga = 1.25 X 16 = 20 2(20 X 20)X 4.275 (10ga)= 26.24#
extended head shoulder

Copper price 1.85/lb mill run 48# @ 1.85		88.80
Fittings + filler rd.		11.83
F/G Mat'l price	$55.00 cdn	55.00
Labor to wrap .6hrs	$21.00	21.00
Labor to fab tank same as Dynasty	$35.00/hr	45.00
M/U on HTLS @ 1.15% X 102.63	221.52	28.89

Cost comparison Mild Steel coated compared with 16ga SS 40 gallon tank.

1) Tank Manufacturing

Material	1	48 X 48" - 102 M.S.	= 64lb	21.00
	2	16 X 16"	= 14lb	5.00
	5	Nipples		7.50
		Welding supply		2.50
				36.00

Compares with 78.00 for 16ga Stainless Steel

cost savings 42.00

Labour to manufacture the tanks would be the same for both materials.

2) Treating

Stainless Steel tank is chemically passivated at a labour cost of approximately 7.50.

Coated tank corrosion resistance depends on the coating. Most coatings are designed for large storage tanks, often cold water, and the inside of the tank needs to be effectively cleaned by sandblasting. The cost of material differs from type of coating to coating and would average between 12.50 to 60.00. It is suggested that to effectively ensure proper cleaning & coating a flanged head may need to be secured. This change in tank manufacture would more than absorb any potential material cost savings. A consideration for using coatings however may be superior corrosion resistance.

MILD STEEL COATED TANK

Problems associated with coating Mild Steel Tanks.

1) Effectiveness - any voids in the application will act as an anode. Typically some lined tanks use a specific anode to overcome this problem.

2) Surfacing preparation - most coatings require sandblasting of surfaces. To be effective this must be done after the tanks are manufactured. This obviously presents considerable difficulties with smaller tanks.

3) Force curing - Many coatings require up to 30 days to cure.

4) Potable water - some coatings are not appropriate.

5) Heat - Many coatings will not stand up to 200ºF for prolonged periods.

6) Application; - There is a problem in how to apply an effective coating with 100% coverage, through a 3/4 nipple. Most tanks could not be guaranteed. A different means of manufacture may need to be considered (see costing comparison SS to Mild Steel tanks).

The following coatings were examined, with all technical data considered.

PLASITE 7156	The Corrosion Service Company Ltd.
Thurmalox No.7	The Dampnex Company.
Tankite III	Devcoe
Protects coat 300	Dudick Corrosion Proff Inc.
Ceramic water tank lining	H.E.B.C.O
Gasiola Sealer	Federal Process Company
Nicrobra 2	Wall Colomony Corp.
Devcon 2	Devcon

FOAMING

The following foams were considered and tested:

Isofoam Rigid

Isofoam 2A (CIL) Polyurethane

Icynene 80 (uthane)

Spinglass (Fiberglass Canada)

Microflex (Marsion) - pipe wrap

Consideration was given to cost of material, performance, and ease of manufacture.

It was found that Rigid Isofoam was the most effective with regard to heat retention. Spinglass and Microflex had least heat retention because of the problems associated with gaps in the wrap around items. Moulds were made for the top and bottom of tanks with Rigid Isofoam utilized. Spinfoam and Microflex was then wrapped around the tank. This still caused unacceptable heat loss.

Rigid Isofoam had one serious problem though. Its expansion was such that it "moved" tanks within jackets which resulted in a deformity of the jackets. It was found that while using Isofoam 2A some extra heat was lost (some .05 to 1% extra per hour depending on tank size). Set-up time was halved. This, along with the lower cost of the Isofoam 2A, resulted in its recommended use. Some 18% of the cost of the tank was reduced by using Isofoam 2A.

JACKETING

Jacketing is designed for 4 purposes:

1) to ensure that the tank remains an integral unit;

2) to remain dent and impact free (shipping and installation);

3) to be as aesthetically pleasing as possible; and

4) costs.

The following finishes and materials were considered:

1) painted 20 gauge steel;

2) PVC jacketing;

3) Filon pipe wrap;

4) Vinyl; and

5) Polystyrene.

In summary the best material is Polystyrene. It had the following advantages:

1) cheapest initial cost;

2) no need to paint;

3) impact and cold resistant;

4) non-corrosive; and

5) aesthetically pleasing - available in many colours and can be easily silkscreened.

The tanks were put together using a polystyrene jacket. A formed galvanized base (which centered the tank) was used on the bottom. A vacuum formed styrene top was utilized as an effective top.

TESTING

Pressure Test

Tanks were tested at 75/150/225/300lbs.
Standard requirements are that the tanks meet 150 PSI for operation testing and 300 PSI for the pressure release valve.

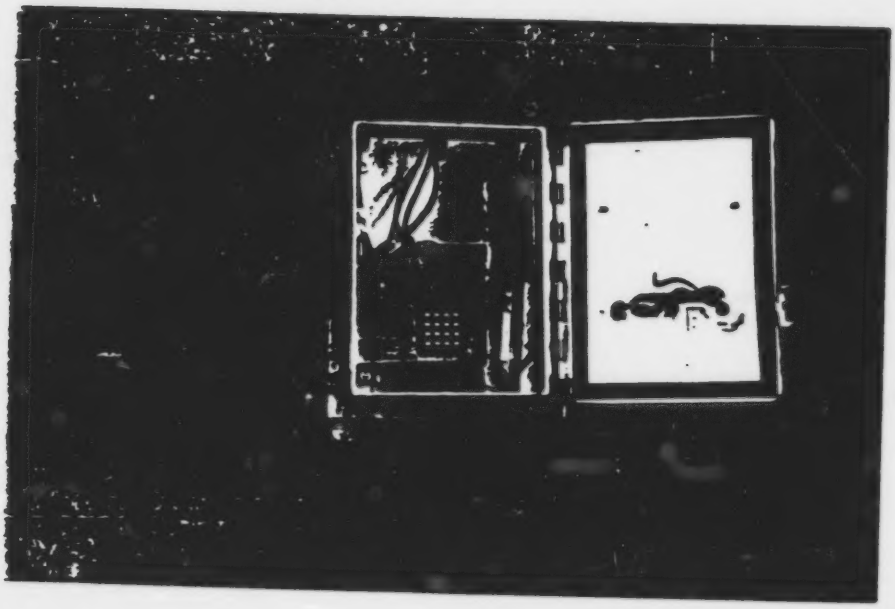
Two stainless steel tanks were tested to 700 lbs pressure inside a specially designed protective cage with no leaking occuring.

Copper wrapped tanks were tested to bursting pressure.
It was of use that they burst at 820 PSI.

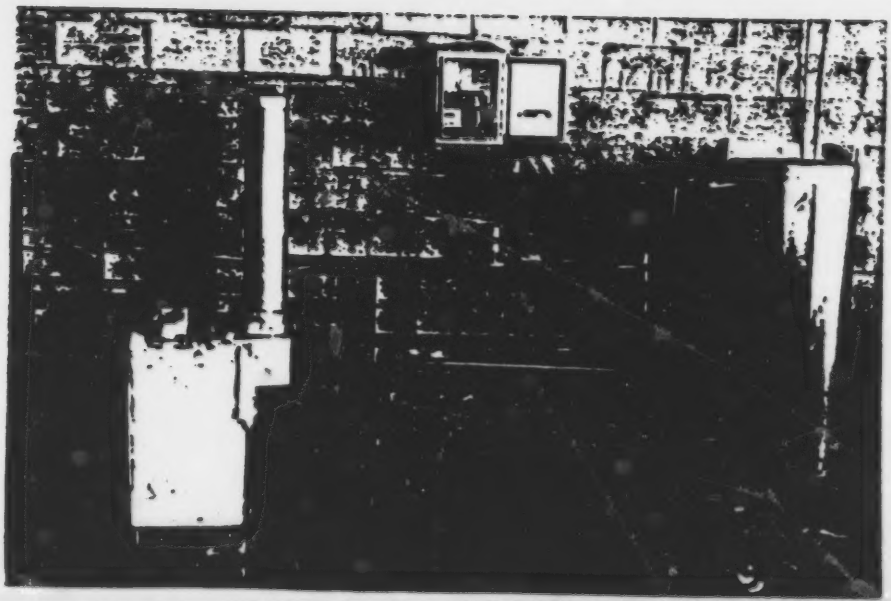
2) PERFORMANCE TESTING

DESCRIPTION

A & R Metals staff set up a 200 MBTU boiler, pumps and tanks as shown in Figure 1. A Campbell Scientific CR21 data logger was set up and programmed to log temperatures and flows at 1 minuite, 5 minute or 10 minute intervals, depending on the test being performed. All thermistor temperature were pre-calibrated in a water bath and were then inserted directly into the water flow for rapid response. Flows were measured by pulse output flow meters. Ken Cooper analyzed and tabulated all data.



Tank Test Facility



RESULTS - TANK TEST:

The results of the test are summarized in Table 1, standardized to a 50 C (90 F) temperature rise and in Table 2, for 10 minute and one hour demand periods. Continuous flow recovery is also shown in Table 1. Tabular and graphical results and a description of the tests for each tank are in Appendix F.

TABLE 1

a) How much water can be drawn in 10 min and 1 hour (based on 21 litres - 5.5 g - per minute).

50 C Temperature Rise:			90 F Temperature Rise:		
TANK SIZE (litres)	DEMAND (Litres) 10 min	1 hour	TANK SIZE (U.S.gal)	DEMAND (U.S.gal) 10 min.	1 hour
114	163	439	30	43	116
151	169	462	40	45	122
227	198	529	60	52	140
303	224	611	80	59	161
379	258	710	100	68	188
454	292	778	120	77	206

b) How much water can be drawn in a continuous flow.

CONTINUOUS FLOW		CONTINUOUS FLOW	
TANK SIZE (litres)	RECOVERY (L/hour)	TANK SIZE (U.S.gal)	RECOVERY (U.S.gal/hr)
114	146	30	39
151	174	40	46

CONTINUOUS FLOW - Cont'd

TANK SIZE (litres)	RECOVERY (L/hour)	TANK SIZE (U.S.gal)	RECOVERY (U.S.gal/hr)
227	230	60	61
303	288	80	76
379	344	100	91
454	402	120	106

Boiler supply at 80 C (180 F) & flow of 11 L/min (2.9 U.S. GPM)

TABLE 2 How much hot water can be drawn in 10 min and 1 hour for 7L/min/12L/min/21L/min.

50 C Temperature Rise:

DEMAND FLOW 7L/min (1.8 U.S. gpm):

TANK (L)	DEMAND (L) 10 min	1 hour
114	97	344
151	97	351
227	97	378
303	97	430
379	97	500
454	97	539

90 F Temperature Rise:

TANK (U.S. gal)	DEMAND (U.S. gal) 10 min	1 hour
30	26	91
40	26	93
60	26	100
80	26	114
100	26	132
120	26	142

DEMAND FLOW 12L/min (3.2 U.S. gpm):

TANK (L)	DEMAND (L) 10 min	1 hour
114	118	370
151	148	360
227	155	430
303	159	499
379	160	587
454	162	645

TANK (U.S. gal)	DEMAND (U.S. gal) 10 min	1 hour
30	31	98
40	39	95
60	41	114
80	42	132
100	42	155
120	43	170

DEMAND FLOW 21L/min (5.5 U.S. gpm):

TANK (L)	DEMAND (L) 10 min	1 hour
114	163	439
151	169	462
227	198	529
303	224	611
379	258	710
454	292	778

TANK (U.S. gal)	DEMAND (U.S. gal) 10 min	1 hour
30	43	116
40	45	122
60	52	140
80	59	161
100	68	188
120	77	206

Boiler supply at 80 C (180 F)
and flow of 11 L/min (2.9 U.S. gpm)

TABLE 2 cont'd...

DOUBLE HEAT EXCHANGER TANKS

50 C Temperature Rise: 90 F Temperature Rise:

DEMAND FLOW 7 L/min (1.8 U.S. gpm):

TANK (L)	DEMAND (L) 10 min.	1 hour	TANK (U.S.gal.)	DEMAND (U.S. gal. 10 min.	1 hour
151	89	401	40	24	106
227	95	488	60	25	129

DEMAND FLOW 12 L/min (3.2 U.S. gpm):

TANK (L)	DEMAND (L) 10 min.	1 hour	TANK (U.S.gal.)	DEMAND (U.S. gal. 10 min.	1 hour
151	160	507	40	42	134
227	162	600	60	43	159

DEMAND FLOW 21 L/min (5.5 U.S. gpm):

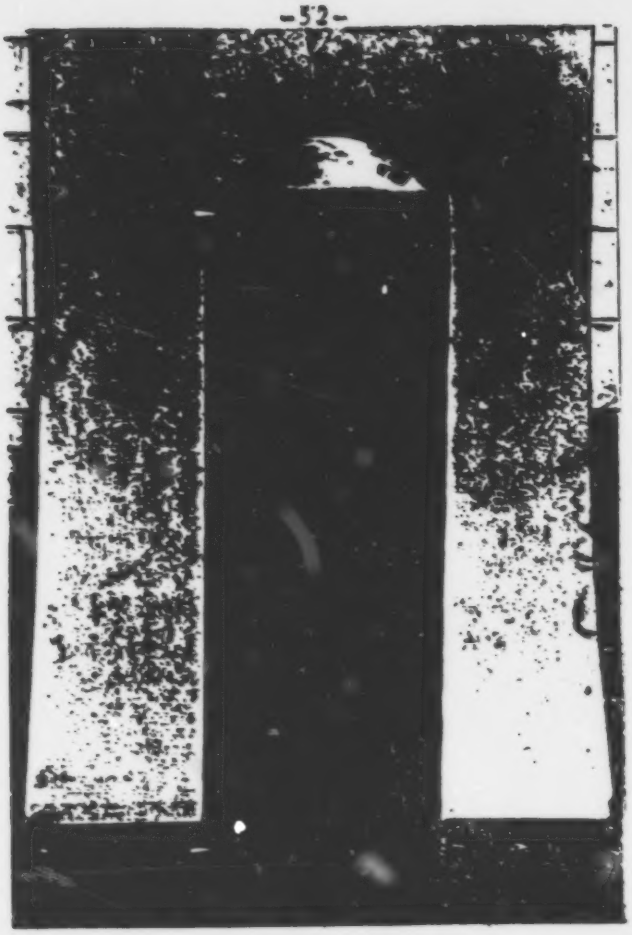
TANK (L)	DEMAND (L) 10 min.	1 hour	TANK (U.S.gal.)	DEMAND (U.S. gal. 10 min.	1 hour
151	270	685	40	71	181
227	284	751	60	75	198

Boiler supply at 80 C (180 F)

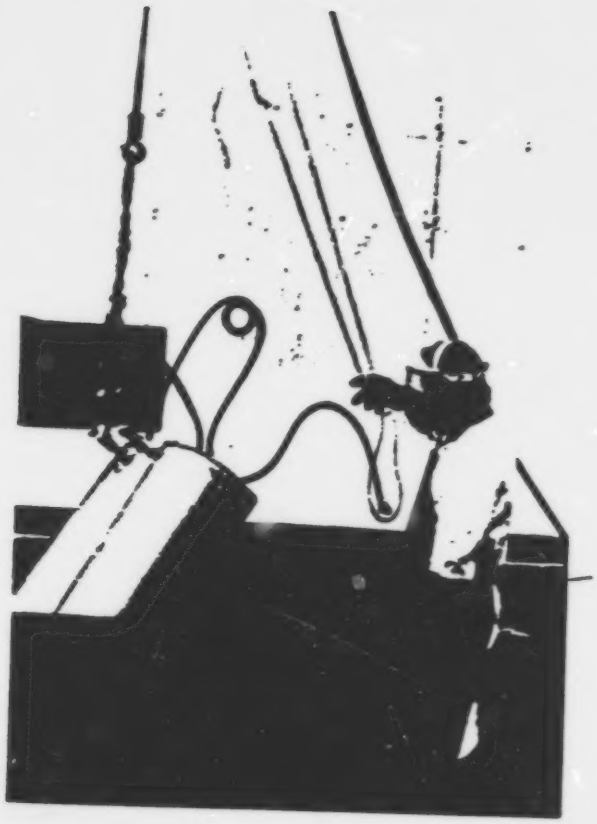
TABLE 3

TANK HEAT RETENTION

(U.S. gal)	% Loss per hour
30	2.6%
40	2.4%
60	2.0%
80	1.6%
100	1.4%
120	1.2%



Fiberglass wrapped copper tanks



PASSIVATION OF TANK

WELDING COIL

COMPLETED TANKS

Discussion

Economics

The practicality of solar heat is largely determined by the annual energy production of a given capital investment. The important characteristic of the capital investment is not the initial value of the investment, but the annual cost for amortiztion of the loan or for establishment of a reserve for equipment replacement. These annual costs are largely determined by the expected lifetime of the equipment and by the performance of the overall system (not the rate at which the collector recovers heat).

For example, if a reserve were to be established, at 10% interest, the capital recovery factor for a five-year expected lifetime would be 0.26; for a ten-year lifetime, it would be 0.16. Thus if the expected life could be increased from five to ten years, the effective annual cost of the energy produced would decline by 39%. Since the primary annual cost of solar heating systems is the recovery of investment, their expected lifetimes are much more important than in conventional systems in which the primary annual cost is purchase of fuel. Furthermore, the high-value components of solar heating systems are passive (collectors, tanks and piping), so the primary factor that determines life expectation is corrosion rather than wear. Since collectors and piping can be made from non-metallic, non corrodable materials and solar tanks cannot, it therefore becomes vitally important that the tanks be made from the material with the least tendency to corrode.

Given that corrosion can be minimized by the selective use of materials, the cost of these materials needs to be taken into account. As water conditions can and do vary from province to province (state to state) and within each province, there is therefore no ideal cost/benefit with the above calculation. An assessment needs to be made of a particular system and its intended performance location. We would highlight that these considerations have to be taken into account. Overall cost may have to be increased to accomodate the use of more resistant materials. The long term reputation and attractiveness of the solar industry depends on honesty in this calculation.

CONCLUSIONS

Given that stainless steel is the recommended material of construction and that the above calculation will determine the type of material to make the storage tank , then this study suggests:

1) 16 gauge stainless steel is an adequate thickness. Thinner gauges may be considered in very passive situations;

2) while the use of a heat exchanger will depend on whether the system is direct or indirect, if in use they should be made of similar materials;

CONCLUSIONS (cont.)

3) all tanks must be passivated and thoroughly tested to ensure that the tank is truely passive;

4) Rigid Isofoam 2A is a preferred foam;

5) jacketing can vary depending on the type of installation. Polystyrene is a preferred foam over other materials;

6) diffusers are required on cold inlets to ensure that jet direction does not effect temperature stratification in the tank; and

7) input size may act as a restriction in large heat exchangers. Consideration needs to be given to using larger input nipples. An estimate of the importance in performance of this approach is given in Appendix G.

CONCLUSIONS

One of the basic objectives of this study was to reduce the cost of the tank utilized in solar systems. A figure of $200 was targetted. The attached table (Table 4) shows comparative cost between tanks made from different types of stainless steel (304, 316, 316L,& 444). The cost of a 304 stainless jacketed tank at $147 is, taking into account normal sales markups, very close to this target ($200.).

In addition the primary criteria required from such tanks has been performance. Their heat retention has been established at 2.6% to 1.2% per hour depending on tank size (30 to 120 U.S. gals)

TABLE 4

Type of Material	Stainless Steel Tank Materials	Stainless Steel Tank Labour	Jacketing & Foam Materials	Jacketing & Foam Labour	Total Cost
304	62	34	36	15	147
316	94	34	36	15	179
316L	98	34	36	15	183
444	126	34	36	15	211

Prior cost using 304, $186. % reduction = 21%

* Based on 40 U.S. gallon tank with one coil.

APPENDICES

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B. CORROSION

C. COPIES OF LETTERS

D BILLS OF MATERIAL & MANUFACTURING SPECIFICATION (STAINLESS STEEL TANKS)

E. COPPER TANKS - SPECIFICATIONS & COST COMPARISON

F. PERFORMANCE DATA - TANKS

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Solar Hot Water System Types

(Courtesy: California Solar Association)

There are seven generic types of solar water heating systems as shown in Figure 1. Depending on the system type, solar heated water may be stored in a tank that also houses electric backup heating element (a "one-tank" system), or in a separate storage tank that feeds into a conventional gas or electric water heater (a "two-tank" system) as shown in Figure 2. Each type of solar water heating system can be characterized as either direct or indirect, depending on whether domestic hot water is heated directly in the collector or indirectly through a heat exchanger. Every solar water heating system, whether direct or indirect, differs solely in its method of freeze protection.

In direct (open-loop) systems, the fluid heated in the collector is normal tap water which flows directly to your household hot water supply. Direct systems should not be used in areas where water is hard or acidic, unless a water softener is installed. Scale deposits can quickly clog the inside of the absorber tubing, and corrosion can render a system inoperable.

In indirect (closed-loop) systems, the heat-transfer fluid can be air, treated water, or some freeze-tolerant liquid such as an antifreeze solution, phase-change fluid, or special oil. The heat picked up by the fluid from the absorber is transferred to the tap water through a heat exchanger. Heat exchangers are typically long

coiled pipe or finned pipe which provides a lot of surface area for the transfer of heat from the solar fluid to storage.

Direct (Open-Loop) Systems

Direct solar water heating systems are defined as being either "active" (requiring a pump) or "passive" (no pumping required). Whether a pump is required depends on the placement of the storage tank in relation to the solar collector.

Active (Pumped) Systems

An active system is used when flexibility is needed in the location of the storage tank. Of course, the shorter the pipe runs between the storage tank and the rest of the system, the lower the heat loss and the more efficient the system. The two types of direct active systems are drain-down and recirculation (Figure 3). Both pump the water from collector to storage when there is enough solar radiation to produce useful heat. During freeze conditions, the collector in a draindown system empties by gravity flow, while a recirculation system periodically pumps warm water from the storage tank to keep the collectors from freezing. Because this method uses up stored or backup energy to prevent freezing, its best application is in climatic zones where frost conditions occur infrequently.

Passive (Non-Pumped) Systems

The simplest direct systems are the integral collector/storage (ICS)

and thermosyphon water heaters (Figure 4). The ICS system has, as its name infers, the storage tank integral with the collector; the absorber surface is the storage tank exterior, and is directly heated by the sun. The solar heated water is delivered to the backup tank by water pressure. Thermosyphon systems have collectors similar to active systems, but the storage tank is located above the collector to induce water circulation by natural convection and gravity. As long as the absorber keeps collecting heat, water warmed in the collector becomes less dense and rises into the storage tank while cooler tank water runs down to take its place. Heated water in the storage tank of both types of systems is delivered to the backup tank by line pressure as hot water is drawn off for household use.

Indirect (Closed-Loop) Systems

Indirect systems are often the best choice for hard water areas and areas most prone to freezing. These systems are designed so that the heat transfer fluid is physically separated from the household water by a heat exchanger. The fluid is either inert or is protected by corrosion inhibitors and antifreeze.

Active (Pumped) Systems

The two basic types of indirect active systems are drainback and heat exchanger systems (Figure 5). They differ in their methods of freeze protection. Drainback systems prevent corrosion and freezing by automatically draining the collector each time the

pump stops operating. They function much like the draindown systems previously described except that the fluid drains back into a holding tank instead of emptying to a septic drain. In freeze protected systems using a heat exchanger, the heat transfer fluid remains in the collector at all times. Antifreeze, phase-change fluid, or heat transfer oils may be used.

Passive (Non-Pumped) Systems

The last system type is an indirect passive thermosyphon system (Figure 6). Although similar to the direct passive thermosyphon system previously described, this system utilizes a closed-loop heat transfer "fluid" which will not freeze. Antifreeze solutions and phasechange fluids such as the refrigerant "Freon" are commonly used. A phase-change fluid vaporizes to a gas in the collector, is forced to rise to the storage tank where it condenses from gas back to a liquid state, giving up its heat of vaporization, and returns to the collector.

Summary

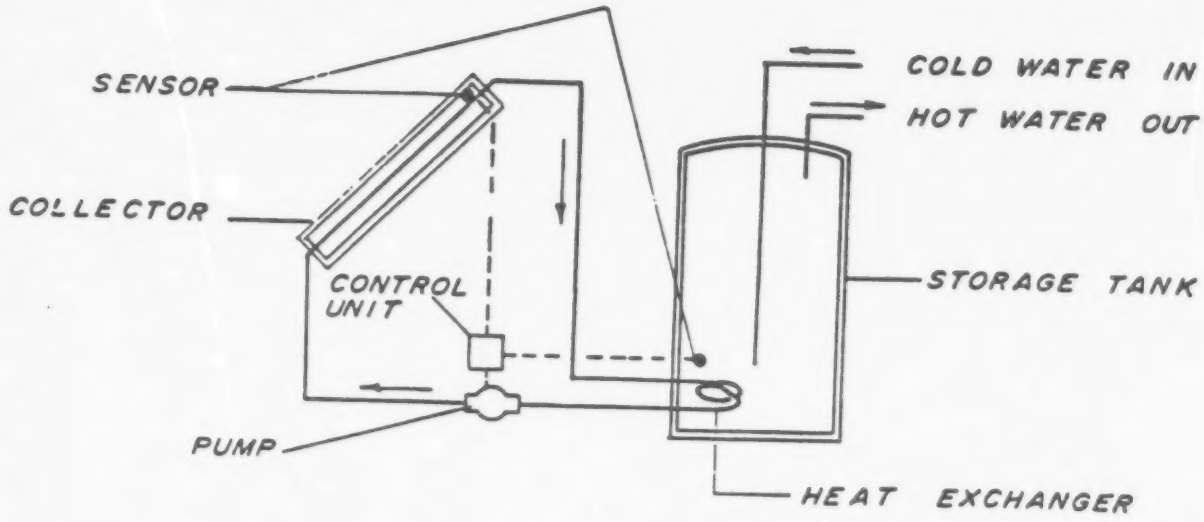
- Solar hot water heating systems are comprised of three major elements: collection devices, storage components and circulation and control components.
- Direct systems are often called "open-loop" systems because the solar system piping uses household potable water as the fluid the collector heats and delivers to the household water supply.
- Indirect systems are often called "closed-loop" systems because

the solar system piping is separate from the potable water supply piping, and a heat exchanger is used to transfer the solar heat to household water.

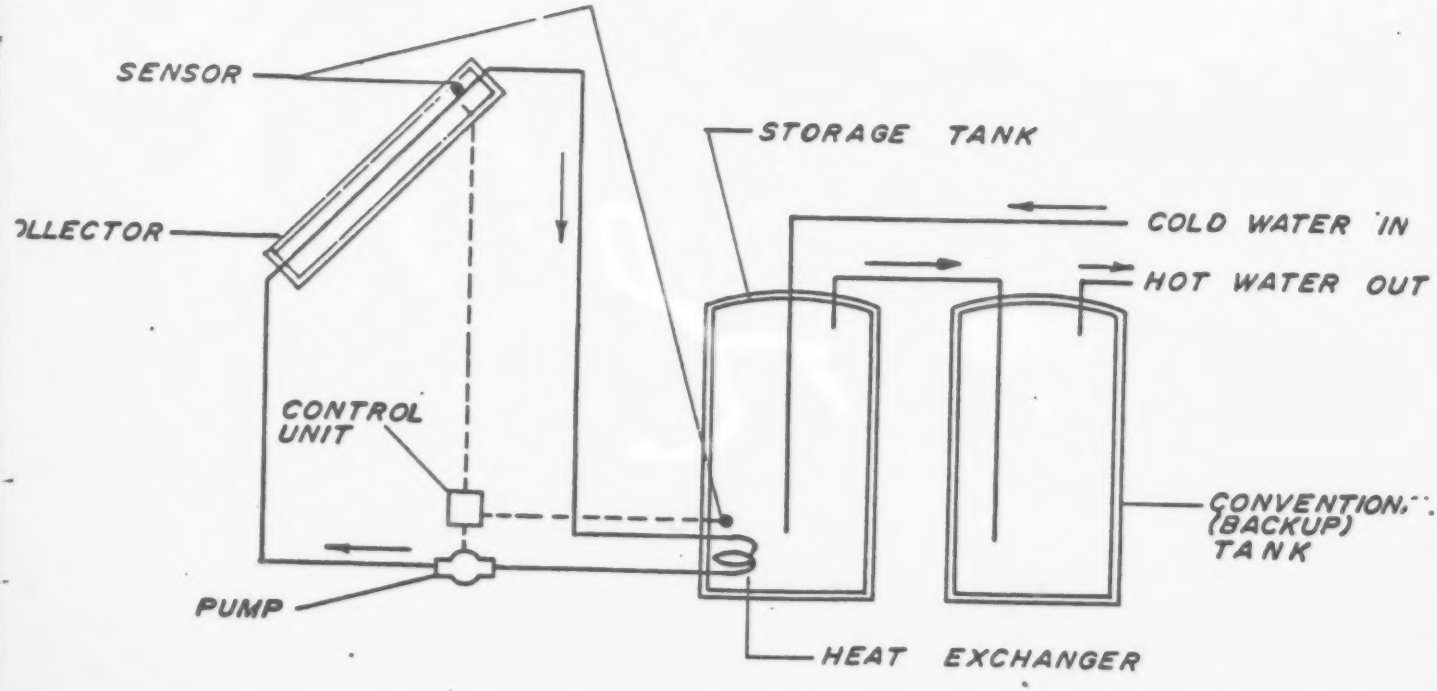
- Active systems use pumps for fluid circulation (direct or indirect).
- Passive systems rely on gravity and natural convection for fluid circulation (direct or indirect).

FIGURE 1

STORAGE METHODS FOR SOLAR HEATED WATER



A "ONE TANK" SYSTEM



A "TWO TANK SYSTEM

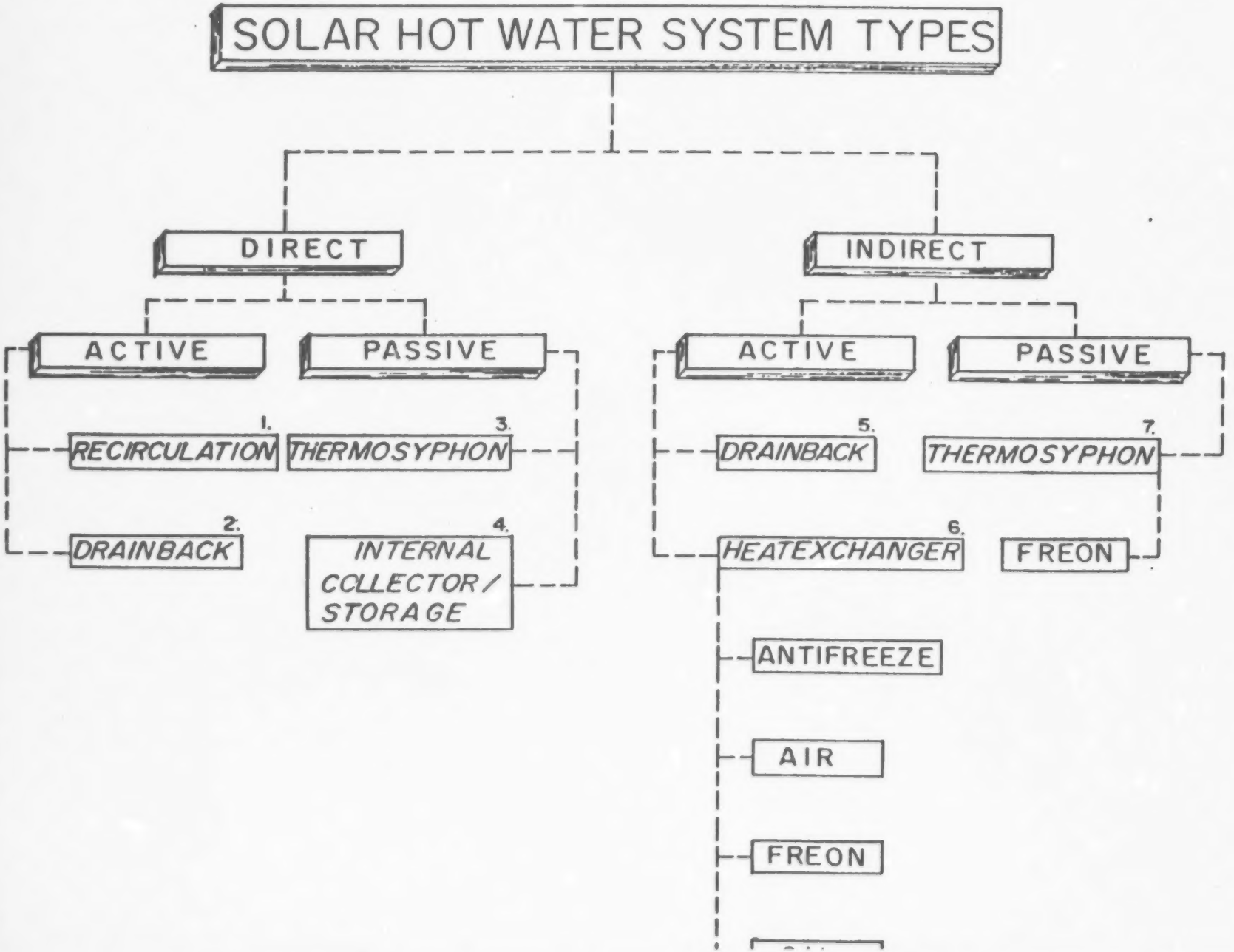
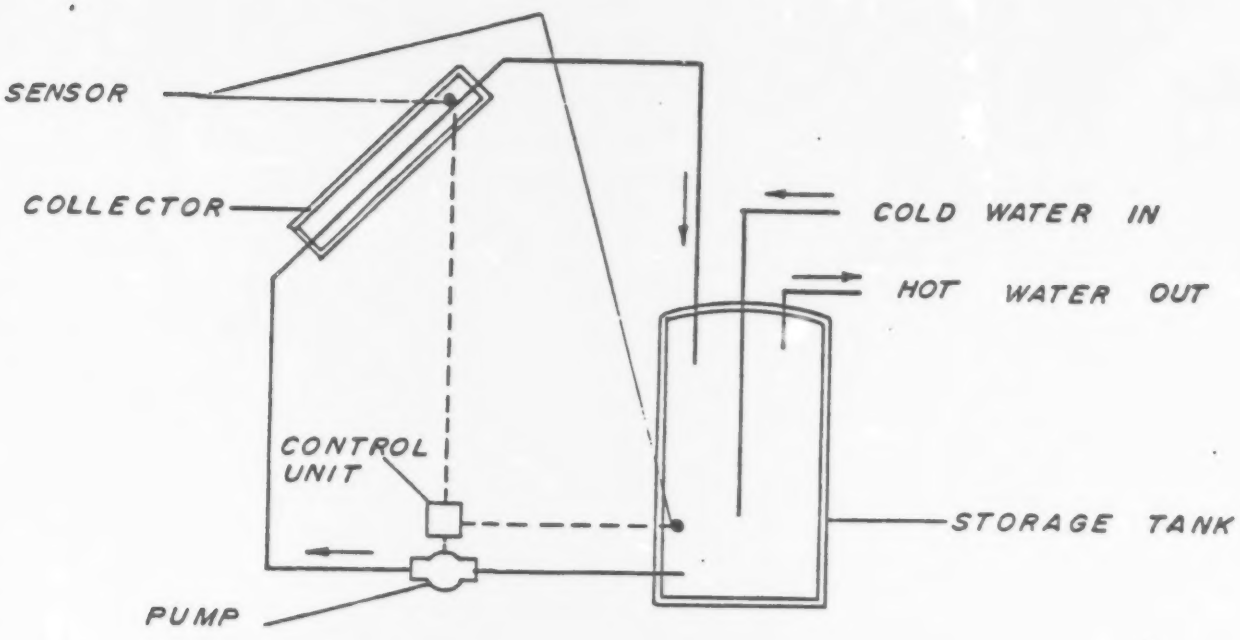

SOLAR HOT WATER SYSTEM TYPES
DIRECT
INDIRECT
ACTIVE
PASSIVE
ACTIVE
PASSIVE
1.
RECIRCULATION
3.
THERMOSYPHON
2.
DRAINBACK
4.
INTERNAL COLLECTOR/ STORAGE
5.
DRAINBACK
7.
THERMOSYPHON
6.
HEATEXCHANGER
FREON
ANTIFREEZE
AIR
FREON

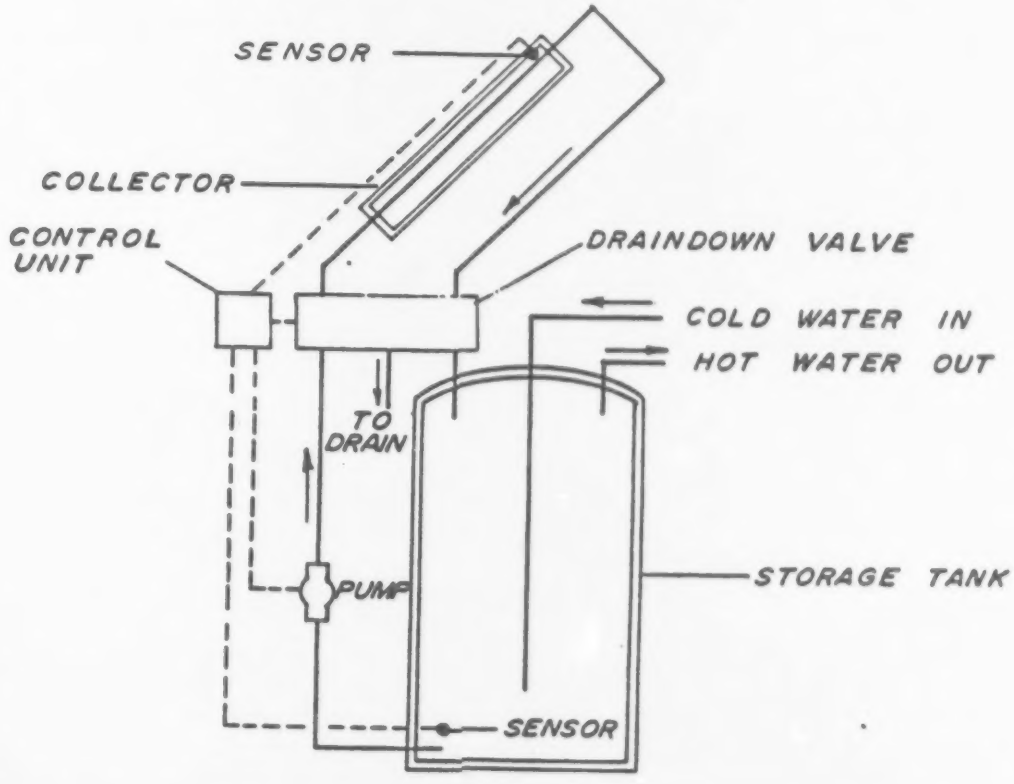
FIGURE 2

FIGURE 3

DIRECT ACTIVE SYSTEMS

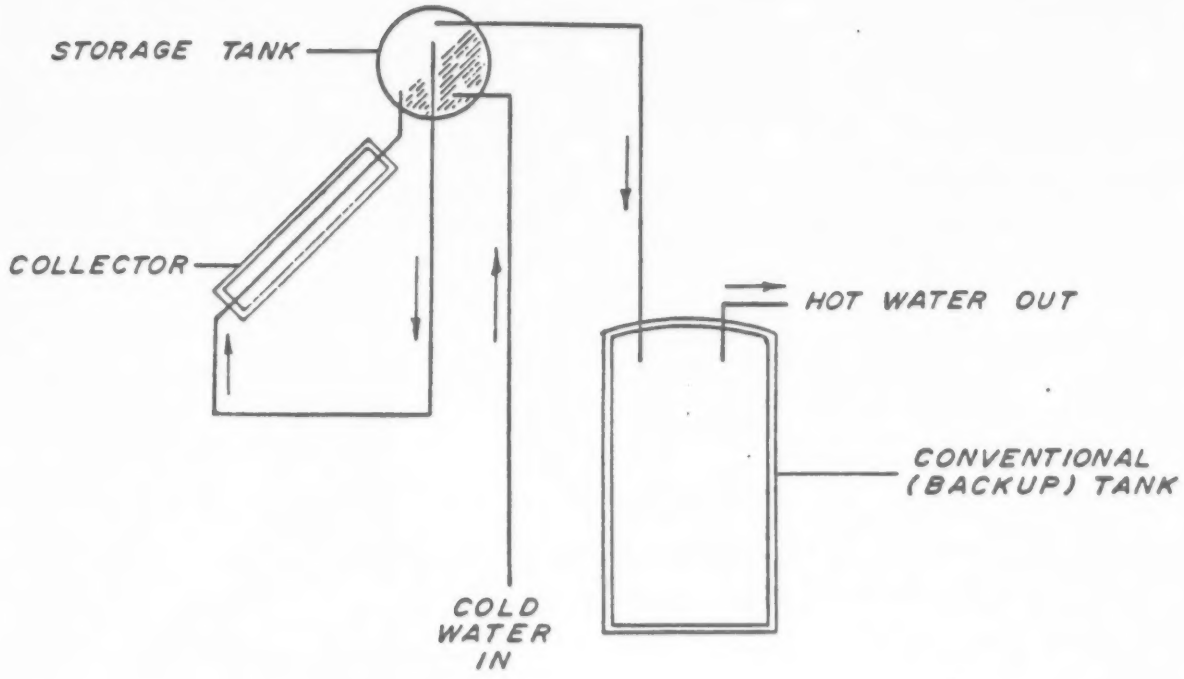


RECIRCULATION SYSTEM No.1.

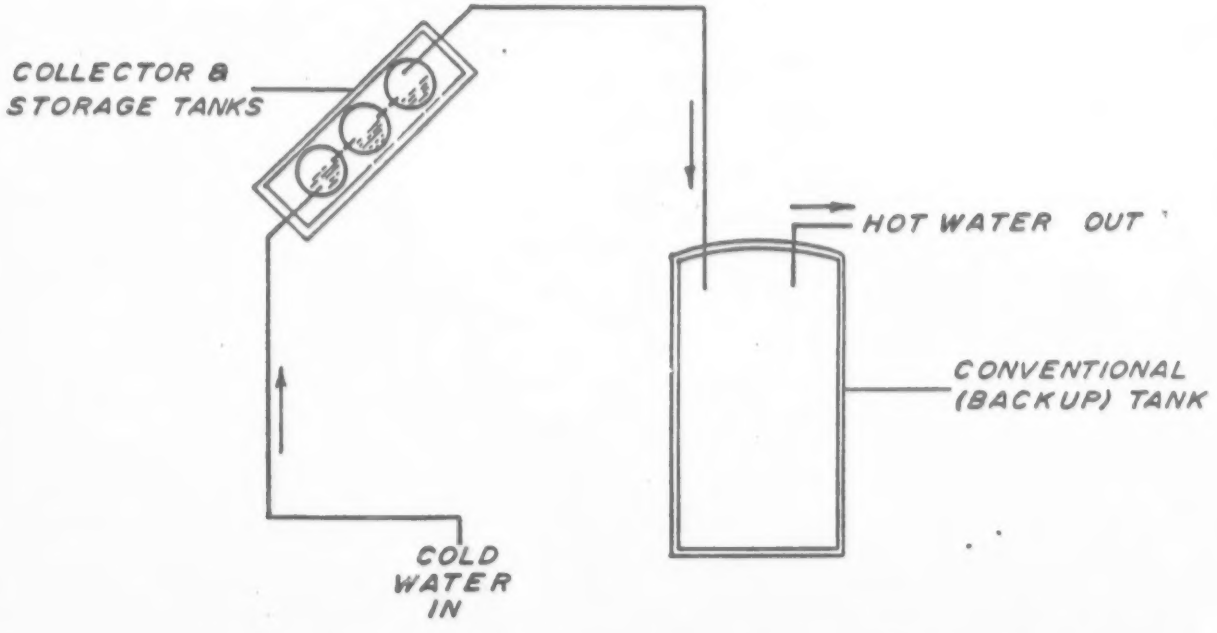


DRAINDOWN SYSTEM No.2.

DIRECT PASSIVE SYSTEMS



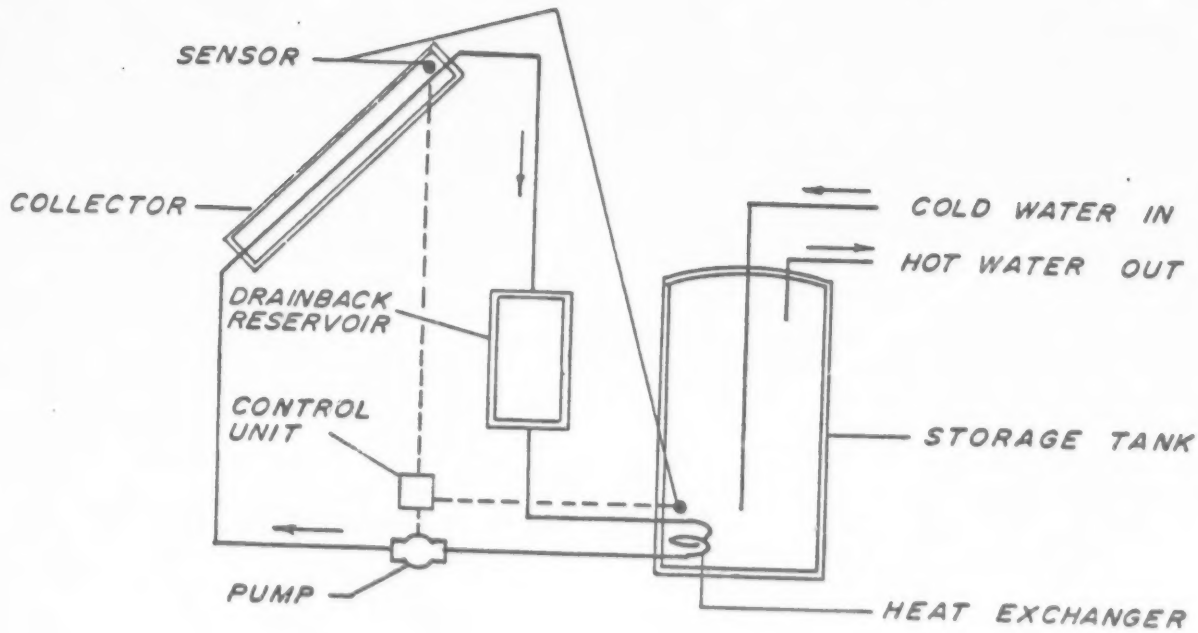
THERMOSYPHON SYSTEM No. 3.



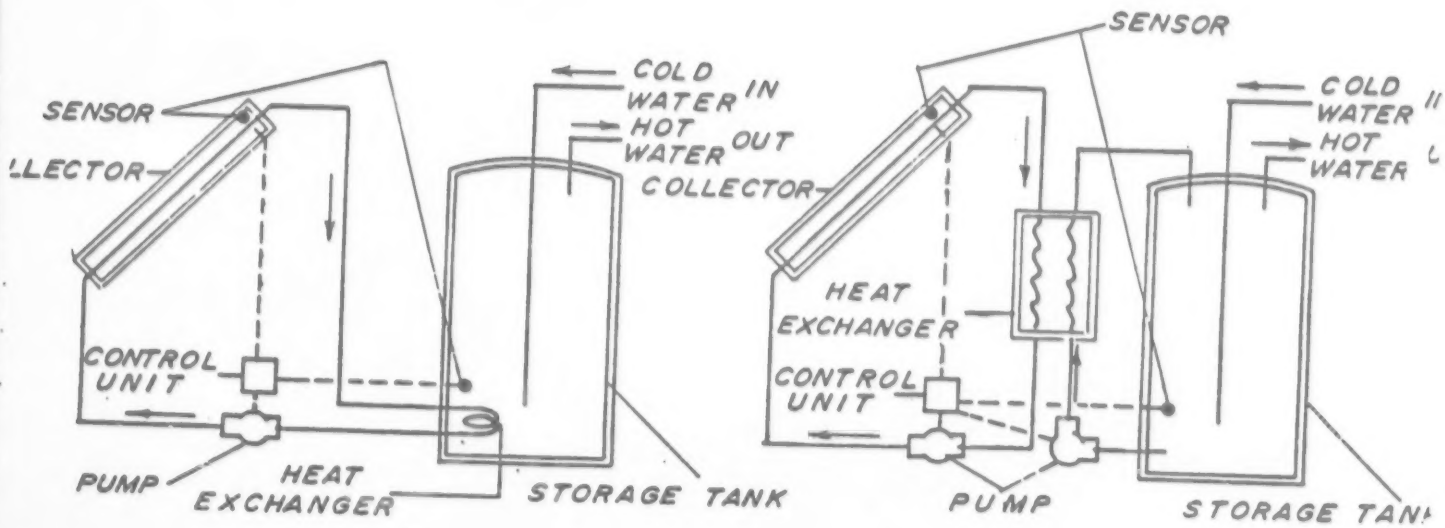
INTERNAL COLLECTOR/STORAGE SYSTEM No. 4.

FIGURE 5

INDIRECT ACTIVE SYSTEMS



DRAINBACK SYSTEM No. 5.

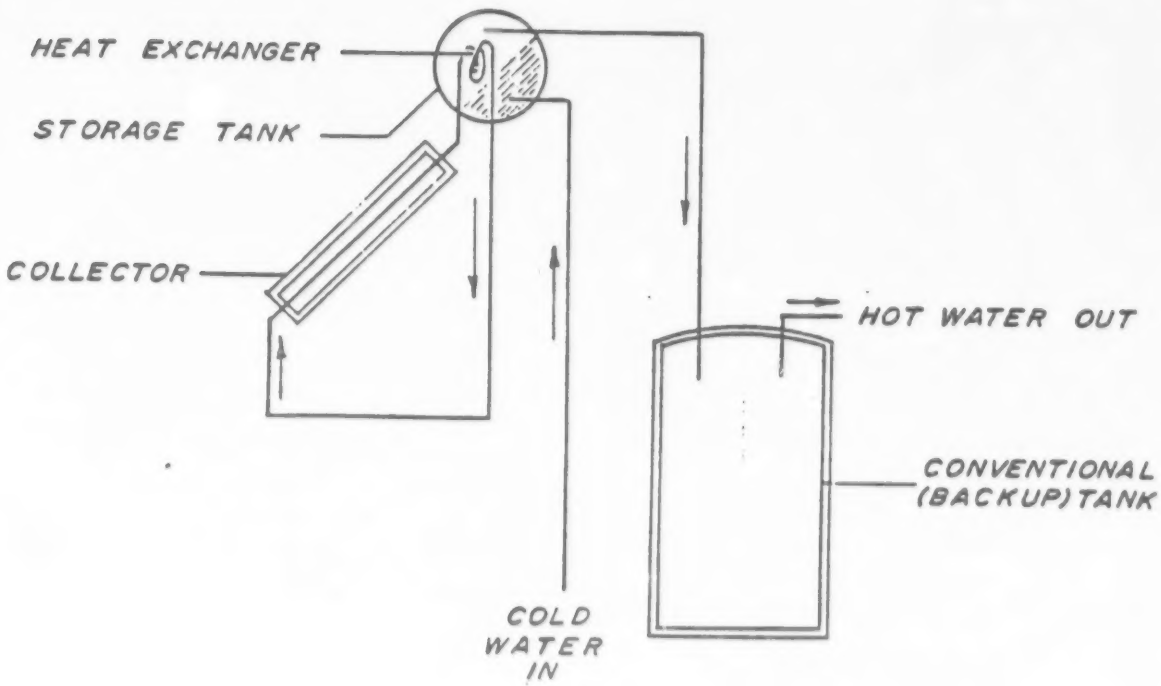


INTERNAL EXTERNAL

HEAT EXCHANGER SYSTEM No. 6

FIGURE 6

INDIRECT PASSIVE SYSTEMS



THERMOSYPHON SYSTEM No.7.

Corrosion Fundamentals

Corrosion Theory

Definition of Corrosion

Corrosion of metal is defined as its deterioration because of a reaction with its environment. A metal typically is a crystal structure in which the metal atoms are held in position by the electrical attraction forces between negatively charged electrons and positively charged nuclei. Often the atoms are arranged in a specific manner called a unit cell which is repeated throughout the crystal structure.

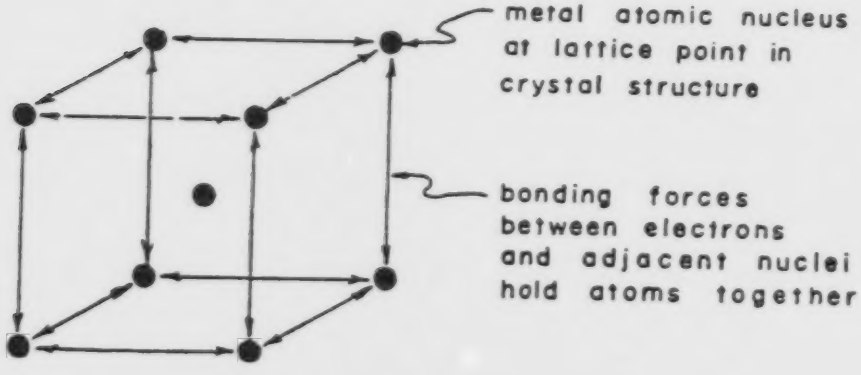

metal atomic nucleus at lattice point in crystal structure
bonding forces between electrons and adjacent nuclei hold atoms together

Figure 1. Typical metal crystalline structure is comprised of a unit cell (body centre cubic in the above example) which is repeated in three dimensions.

Corrosion is the loss of the bonding force between electrons and nuclei which allows a metal atom to leave the metal crystalline lattice and enter the electrolyte as a positively charged ion. The electrolyte is any liquid phase environment,

but for the purpose of this work it is always solar heated water.

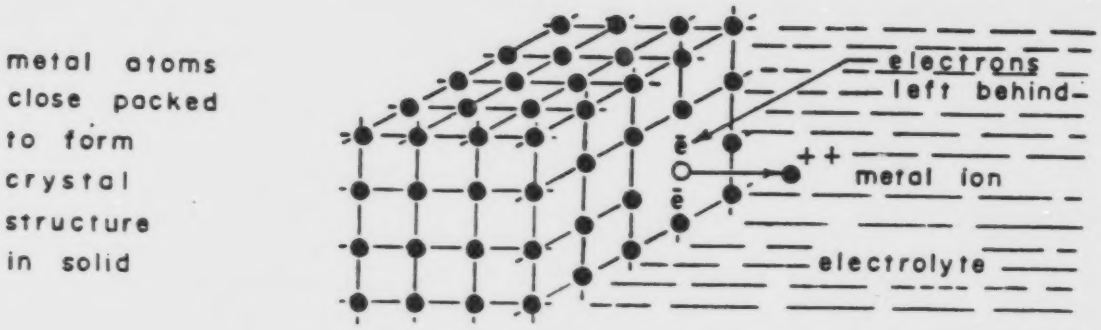


Figure 2. Corrosion occurs when a metal atom loses its bonding force electrons and becomes a positively charged ion.

The corrosion process is, therefore, an electro chemical reaction whose general form may be written as follows:

$$M^{\circ} \text{ --------> } Mn^{+} \quad {}^{+}ne$$

(Metal atom) (Metal ion) (Electron)

Where 'n' equals the number of electrons lost by the atom

For iron or carbon steel the corrosion reaction is normally

$$Fe^{\circ} \text{ --------> } Fe^{+} \quad {}^{+}2e$$

(Iron atom) (Iron ion) (Electrons)

All corrosion reactions are oxidation reactions since the valence change is in the positive direction. Any electro chemical reaction in which an element changes valence in the positive direction is by definition an oxidation reaction.

Free Energy of Corrosion

All electrochemical reactions require energy to proceed and the energy for the corrosion (oxidation) process originates during the extraction of the metal from its ore. As shown in Figure 3 iron ore (iron oxide) is subjected to heat energy to extract the iron atom from the iron ore at the steel mill.

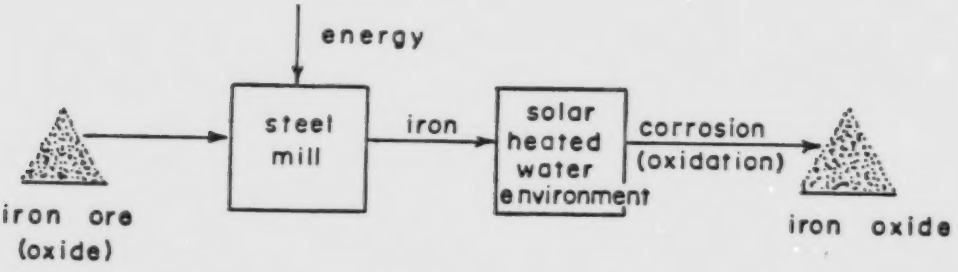


Figure 3. Corrosion is extraction metallurgy in reverse.

When the resulting iron or steel in the form of a pipe, tank or fitting is placed into a solar heated water environment, the metal reacts with the environment to again form a metal oxide. This can be considered extractive metallurgy in reverse. The energy which drives the oxidation reaction is called Gibb's free energy (Delta G°).

All metals have different free energies and hence different tendencies to oxidize (corrode). Table 1 lists the Gibb's free energy change to form one mole of metal oxide for various metals. The metals with the largest negative free energy changes are the metals with the greatest tendencies to corrode.

Corrosion (oxidation), therefore, occurs spontaneously when a metal such as carbon steel or copper is exposed to an aqueous environment and is driven by the Gibb's free energy locked into the metal during the extractive metallurgical process.

Table 1

Standard free energy (Delta G°) of formation of some oxides in KCAL/Mole of oxide at 27°C (1)

Oxide	Free Energy	Metal	Corrosion Tendency
Al_2O_3	-377.6	Aluminum	Greatest
Cr_2O_3	-236.7 (at 277°C)	Chromium	
SiO_2 (Quartz)	-197.3	Silicon	
MgO	-136.5	Magnesium	
ZnO	-76.2	Zinc	
FeO	-54.6 (at 227°C)	Iron	
PbO	-45.0	Lead	
Cu_2O	-34.6	Copper	
Ag_2O	-2.55	Gold	Least

Electromotive Force Series

The free energy change of a metal during oxidation is also related to its electrical potential by the following equation:

$$\text{delta } G^\circ = -nFE$$

Where n = valence change during oxidation

F = Faraday's constant of 96,000 coulombs

E = electrical potential (volts)

delta G° = change in Gibb's free energy during oxidation

Therefore, all metals can be arranged in terms of standard electrical potential which reflects the amount of Gibb's free energy available to power the corrosion reaction.

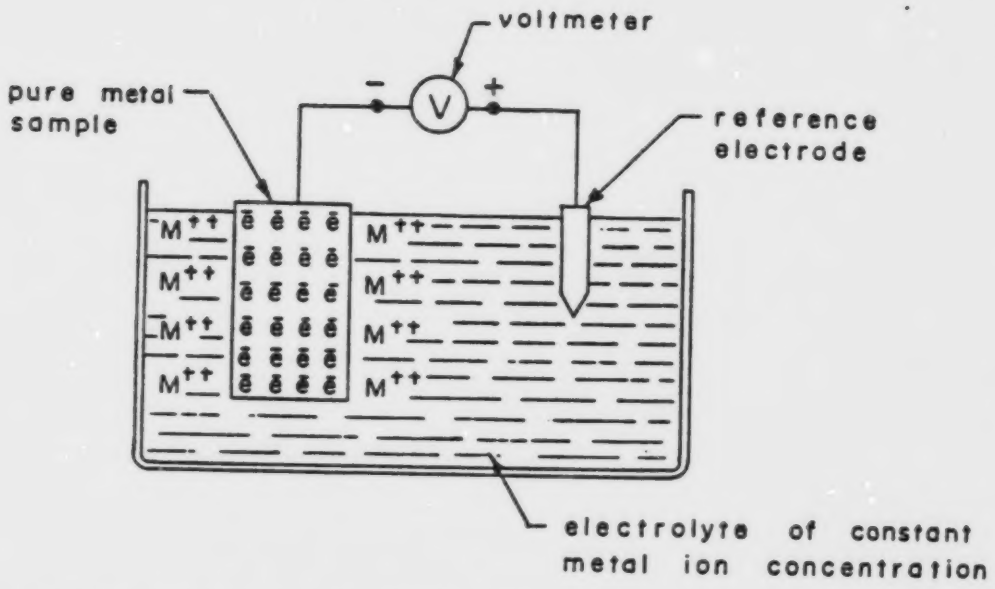


Figure 4. Measurement of electrochemical corrosion potential difference

The electrical potential of a pure metal sample can be measured using a high resistance dc voltmeter and a reference electrode as shown in Figure 4. When this procedure is repeated at standard temperature and standard metal ion concentration in the electrolyte for many metals then a series called the electromotive force series can be developed as in Table 2. The standard reference electrode used for these measurements

is a standard hydrogen electrode.

Here again the metals with the largest negative value are the metals with the greatest tendency to corrode when placed in an aqueous environment. The metals at the bottom of the series (noble end) such as silver, gold, and platinum are noted for their corrosion resistance.

Table 2

Electromotive Force Series (2)

Electrode Reaction	Standard Hydrogen Electrode Potential E° (Volts) 25°C		Metal
$Mg = Mg^{++} + 2\bar{e}$	-2.34	active	Magnesium
$Al = Al^{+++} + 3\bar{e}$	-1.67		Aluminum
$Zn = Zn^{++} + 2\bar{e}$	-0.762		Zinc
$Cr = Cr^{+++} + 3\bar{e}$	-0.71		Chromium
$Fe = Fe^{++} + 2\bar{e}$	-0.440		Iron
$Cd = Cd^{++} + 2\bar{e}$	-0.402		Cadmium
$Co = Co^{++} + 2\bar{e}$	-0.277		Cobalt
$Ni = Ni^{++} + 2\bar{e}$	-0.250		Nickel
$Sn = Sn^{++} + 2\bar{e}$	-0.136		Tin
$Pd = Pd^{++} + 2\bar{e}$	-0.126		Lead
$H_2 = 2H^{+} + 2\bar{e}$	0.000		Hydrogen
$Cu = Cu^{++} + 2\bar{e}$	0.345		Copper
$Cu = Cu^{+} + \bar{e}$	0.522		Copper
$Ag = Ag^{+} + \bar{e}$	0.800		Silver
$Pt = Pt^{++} + 2\bar{e}$	1.2		Platinum
$Au = Au^{+} + \bar{e}$	1.68	noble	Gold

Practical Galvanic Series

The electromotive force series can only be reproduced in the laboratory using pure metal samples under carefully controlled conditions and therefore has limited practical value compared with the practical galvanic series in Table 3. This series arranges commercially available metals and alloys exposed to a seawater electrolyte in order of their solution potentials with respect to a copper-copper sulphate electrode.

When two metals of different solution potential are interconnected in an electrolyte the metal with the largest electro-negative potential will corrode. The two metals are said to produce a galvanic corrosion cell.

Table 3

Practical Galvanic Series (3)

Metal	Volts $CuCuSO_4$ Electrode	Corrosion Tendency
Commercially pure magnesium	-1.75	Greatest
Magnesium alloy (6% Al, 3% Zn, 0.15% Mn)	-1.60	
Zinc	-1.10	
Aluminum alloy (5% Zinc)	-1.05	
Commercially pure aluminum	-0.80	
Mild steel (clean and shiny)	-0.50 to -0.80	
Mild steel (rusted)	-0.20 to -0.50	
Cast iron (not graphitized)	-0.50	

Table 3 - Continued

Metal	Volts $CuCuSO_4$ Electrode	Corrosion Tendency
Lead	-0.50	
Mild steel in concrete	-0.20	
Copper, brass, bronze	-0.20	
High silicon cast iron	-0.20	
Mill scale on steel	-0.20	
Carbon, graphite, coke	+0.30	Least

The galvanic series might suggest that the entire surface of all active metals would spontaneously disintegrate when exposed to an electrolyte. This, however, is not the case, as corrosion typically occurs at discrete locations and on particular metals only. The discreteness of the corrosion action is a result of differences on the metal surface from location to location or differences in the electrolyte from one location to another.

Table 4

Standard Reference Electrodes

Electrode	Potential in Volts (a)
Saturated Calomel	+0.242
Copper-copper Sulphate (saturated)	+0.316
Standard Hydrogen	0.000

(a) Potential to standard hydrogen electrode at 25°C

The standard hydrogen electrode is awkward to use in a practical sense. The conversion of different reference electrodes is shown in Table 4 and illustrated by the following example: To convert -0.800 Volt $CuCuSO_4$ to standard hydrogen electrode having a potential of zero, it is necessary to add +0.316 making it -0.484 Volt versus hydrogen.

The Corrosion Cell

The corrosion cell can be established in many ways. Table 1, 2 and 3 have listed the free energy, difference in solution potential and the differences at discrete locations both on the metal surface and in the solar heated water electrolyte for (oxidation) corrosion to occur. This is only one-half of the reaction. All corrosion cells have four components:

1. An electrode which corrodes (oxidizes) which are called the anode.
2. An electrode where a reduction reaction occurs called the cathode.
3. An isolated path external to the cell electrolyte, usually the metallic tank wall itself.
4. An electrolyte common to both anode and cathode, in this case the solar heated water.

For corrosion to occur then, there must be a release of electrons at the anode and the formation of metal ions through oxidation. There must be, at the cathode an acceptance of

electrons. The two reactions must occur simultaneously and at the same time. The corrosion cell can be established in many ways. Concentration variations or differences in the solar heated water or in the metal itself may result in a different demand for electrons. Any time a metal is in direct contact with water corrosion will occur. The rate and type of corrosion are functions of many parameters.

Differences in oxygen concentrations in the electrolyte or of any other substance involved will change the electro-negative potential as shown by the nernst equation. (4)

$$E = E^{\circ} + \frac{2.3\ RT}{nF}\ \text{Log}\ \frac{Aox}{Ared}$$

For the general half-cell equation.

Oxtne = Red

Where Aox = the activity of the oxidized form of the relevant substance

n = the number of moles of electrons transferred in the reaction per mole of Ox

Ared = the activity of the reduced form of the substance

In dilute solutions, such as solar heated water, the activities can be considered equivalent to concentrations.

The E for a reaction is the difference between the E's calculated for the two half-cells, and therefore changes with concentration. An electrochemical cell can be set up, then, by a concentration difference between the anode and the cathode sites; there would be a potential difference produced by those concentration differences. This can be illustrated as in Figure 5, which shows corrosion of a piece of iron in contact with water.

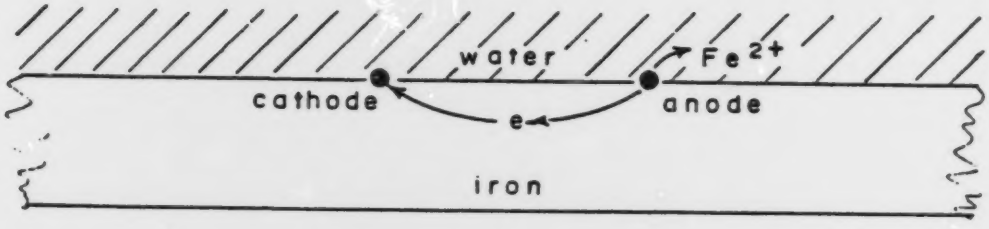


Figure 5 (a). The corrosion cell (iron).

The initiation of corrosion occurs because of some inhomogeneity in the metal surface.

For example: - a variation in crystal structure.
- a small crevice or scratch.
- a piece of mill scale or weld slag.
- a spot of discolouration or rust.

This starts corrosion at the anode and transfers electrons to the cathode.

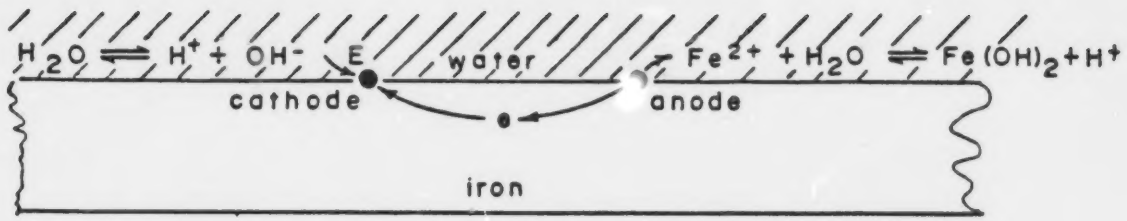


Figure 5 (b). The corrosion cell (iron).

There they are accepted by H^+ to form H_2 as shown in Figure 5 (b). The Fe^{2+} that was shown as going into solution in Figure 5 (a) could react with water to form the hydroxide, $Fe(OH)_2$, which is somewhat soluble, and thus release H^+. The hydrogen formed at the cathode diffuse away from the surface slowly, or might adhere and limit further reaction.

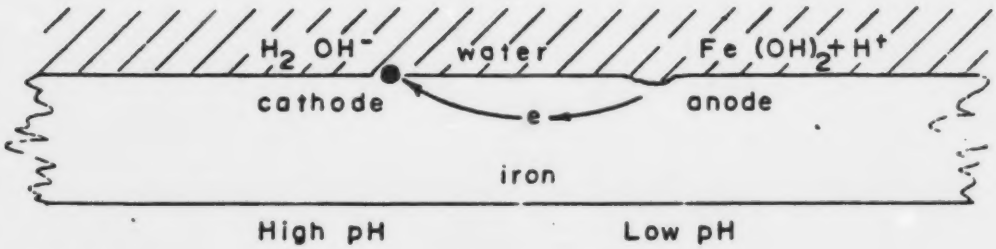


Figure 5 (c). The corrosion cell (iron).

The presence of OH^- near the cathode and H^+ near the anode leads to a concentration for both H^+ and OH^- as shown in Figure 5 (c). This creates an even greater difference and accelerates the

corrosion rate.

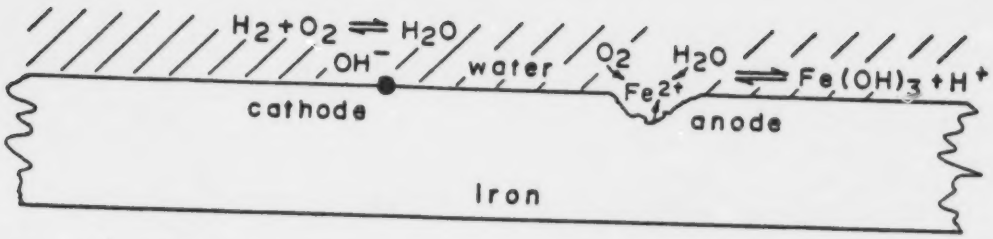


Figure 5 (d) The corrosion cell (iron).

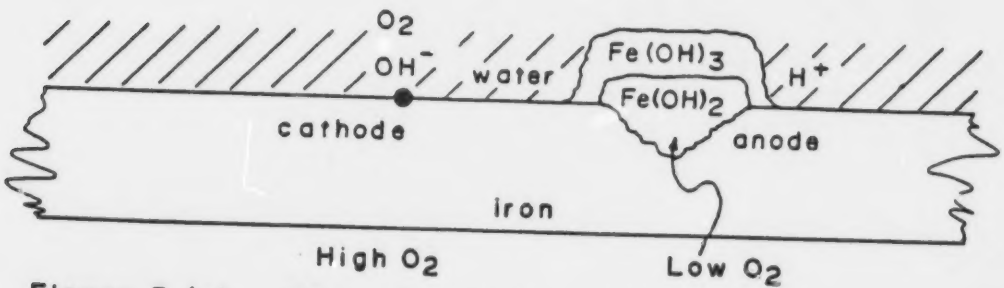


Figure 5 (e) The Corrosion cell (iron).

If the water is oxygenated, as in the solar open loop system types or to a lessor extent in the solar closed loop system types, the oxygen reacts with the hydrogen at the cathode to form water and with Fe^{2+} at the anode to produce the very insoluble $Fe(OH)_3$. This precipitates at the surface immediately and shuts off the flow of O_2 to the Fe^{2+} that is being released at the anode. This creates another concentration differential; this time in terms of O_2, shown in Figure 5 (d) and 5 (e). The build-up of $Fe(OH)_3$ on the anode concentrates the further reaction at that site. This results in corrosion pitting and the growth of a tubercule. The oxidation of iron in the pit produces Fe^{2+} which is restricted to the site by the insoluble protective

layer of $Fe(OH)_3$. Diffusion of water into the tubercule leads to an increase in the internal pressure. This ultimately results in the rupture of the tubercule and release of $Fe(OH)_2$. It is rapidly oxidized to $Fe(OH)_3$ by the oxygen present and precipitates to increase the size of the tubercule.

The removal of hydrogen from the cathode also accelerates the corrosion rate by allowing the cathodic reactions to occur more readily. The corrosion rate is frequently limited by the rate at which oxygen is available at the cathode to react with H_2. This was utilized by Donahue (5) in an equation relating the corrosion current to the mass transport of oxygen.

$$i = nFKC$$

Where i = limiting current density

n = moles electrons/mole reacting substance

F = Faraday's constant

K = mass transport rate constant

C = oxygen concentration

All corrosion which occurs in an aqueous environment, such as solar heater water, does so at the anode. What happens at the cathode is of greater consequence in controlling corrosion.

Faraday's Law

As the weight of an atom is predominantly in the nucleus and the metal ion contains the atomic nucleus then it follows that

the corrosion process results in a metal loss. The amount of weight loss is related to the charge transfer by Faraday's law which states:

$$W = \frac{MQ}{Fn}$$

Where W = weight of metal dissolved (grams)

F = Faraday constant (96,500 coulombs of electrical charge per equivalent)

M = relative atomic mass of metal (grams)

n = valence change in oxidation

Q = total charge transferred (coulombs)

Faraday's law, therefore, relates to weight loss at the anode site with the charge transfer between the anode and cathode of a corrosion cell. It should be noted that weight loss predicted by Faraday's law is confined to the anode site only but is not always achieved in practice.

Corrosion Mechanisms

The Nature of Corrosion Cells

Natural corrosion of a metal can occur spontaneously owing to the internal Gibb's free energy which drives the corrosion reaction and which is an inherent thermodynamic property of any metallic material. Given this premise, then one would expect all metallic materials to disintegrate extensively and quickly upon contact with the solar hot water environment. The fact that such catastrophic failures are not more prevalent is a result primarily of the relatively slow rate of the electro-

chemical reactions which take place in a corrosion cell.

As shown in Figure 5, corrosion occurs principally at the anode of a corrosion cell composed of a cathode, electrolyte, and an electronic conductor. Not all corrosion cells are internally driven nor do all corrosion cells require dissimilar metals. Several environmental, electrical and metallurgical factors cause the formation of corrosion cells and therefore control corrosion activity. These basic factors are depicted in Figure 6.

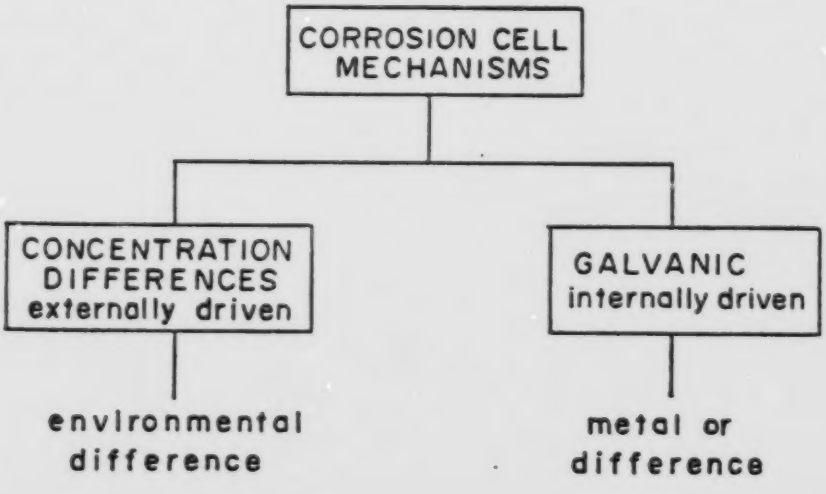


Figure 6. Fundamental factors causing corrosion cells to develop.

It is important to note that galvanic cell activity is produced exclusively from the loss of internal Gibb's free energy. The underlying common factor is that a basic difference in either electrical voltage, environment, metal type or metallurgy

exists. All corrosion cells can be classified by a difference in one or more of these basic factors.

Galvanic Corrosion Cells

From Table 3, the practical galvanic series, it can be seen if two dissimilar metals are placed in an electrolyte, a potential difference will exist between them. If these metals are then connected together so that a negative charge can transfer from one to the other, corrosion (oxidation reaction) will continue to occur at the anode (the most electro-negative metal) and a reduction reaction will occur at the cathode (the least electro-negative metal). For example, the interconnection of a steel solar hot water tank to a copper household plumbing system will result in a corrosion cell as illustrated in Figure 7.

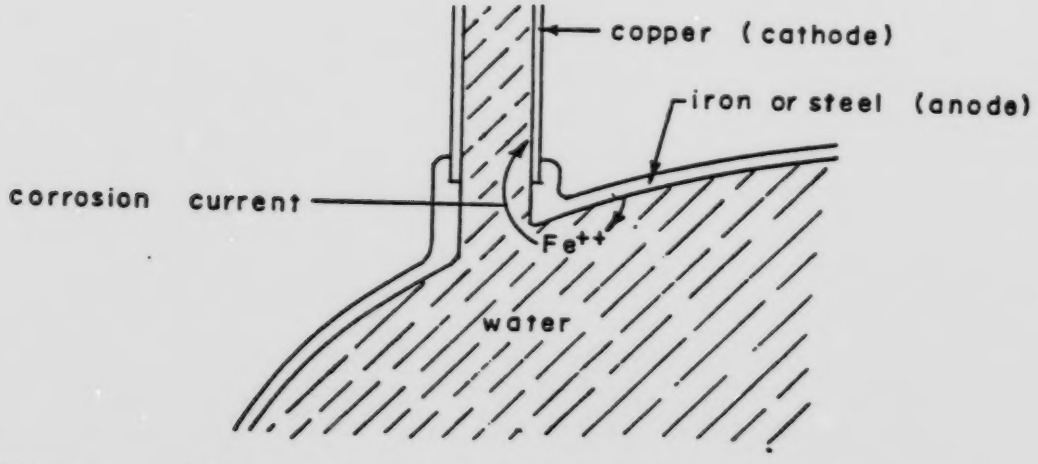
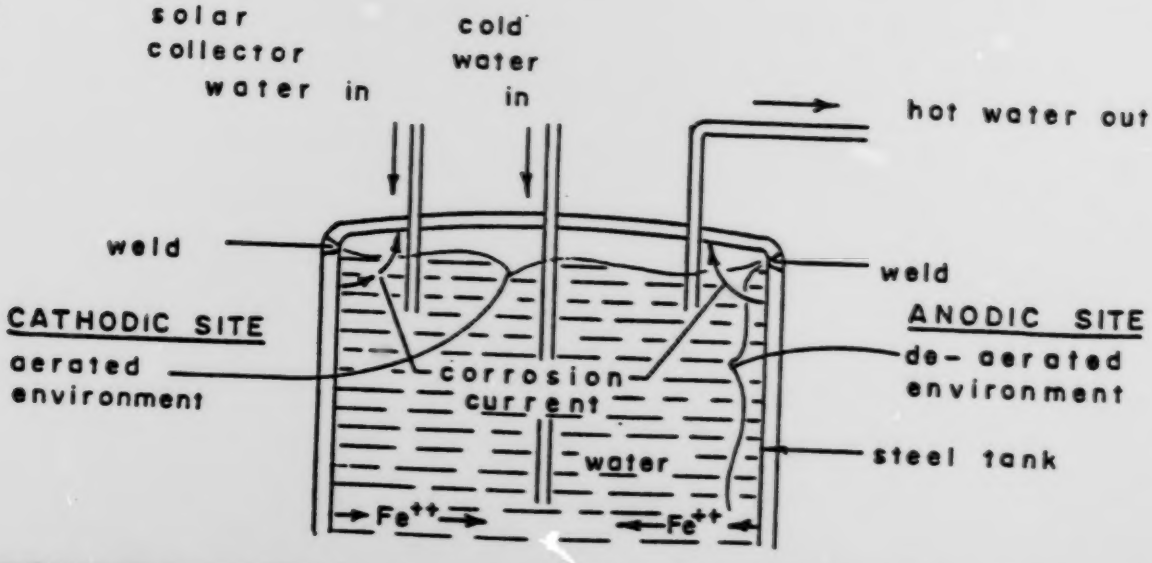


Figure 7. Dissimilar metal corrosion cell.

The initial potential difference between steel tank and the copper pipe could be as much as 600 Millivolt (800 Mv - 200 Mv) as indicated in Table 3. When the two metals are connected then this potential difference will result in a corrosion current flow both in the water and in the metal paths. Because steel is the most electro-negative of the two metals, it will corrode releasing iron ions into the water. The total weight loss from the steel tank depends on the corrosion current and time as related to Faraday's law.

Corrosion can also result from a difference from location to location on the metal tank. For instance, a metal such as steel, placed in an aerated (oxygen rich) electrolyte will have a potential which is less electro-negative than another location on the same metal in a de-aerated environment. This type of corrosion is often manifested on tank walls as illustrated in Figure 8.



The oxygen supply near the surface of the water in the tank is understandably greater than at the bottom of the tank. This oxygen concentration difference influences the corrosion activity in the following manner.

In neutral or alkaline environments the oxygen participates in the following reduction reaction at the cathode sites:

$$O_2 + 2H_2O + 4e \text{ --- } 4\ OH^-$$

In this reduction reaction four electrons are removed from the metal to form four hydroxyl ions. The removal of these electrons depletes the negative charge concentration at the cathode thus allowing two more iron atoms to corrode at the anode. A corrosion cell caused by differential aeration results in the anode being located in the relatively oxygen starved region of the tank.

The examples of corrsion cells discussed so far have all involved relatively large and discrete electrodes located measurable distances apart. They result in corrosion at discrete locations, namely, on the anodes. In contrast, general corrosion activity is relatively evenly distributed over a structure is usually caused by many small corrosion cells in which the anode and cathodes are only micro-inches apart. These micro-corrosion cells are caused by minute metallurgical differences in the crystal structure of the individual metal.

Typical metallurgical defects include foreign atoms in the crystal grains, dislocation of the atomic lattice, and orientation of the crystal grains with respect to each other and with respect to the aqueous environment. One interesting feature of these micro-corrosion cells is that the anode and cathode sites frequently move about such that a cathode site may temporarily exist on a former anode site and vice-versa. This is in marked contrast to the other galvanic corrosion cells in which the anode and cathode sites remain relatively immobile.

Stress Corrosion Cracking (SCC)

Stainless steels are susceptible to stress corrosion cracking particularly in the presence of chlorides in the solar heated water environment. Stress corrosion cracking is an anodic process. Stainless steels are also susceptible to pitting and crevice corrosion. Almost without exception very thin oxide films form almost instantaneously on the surface of all metals exposed to moisture. Anything which causes the natural protective film to be disturbed or ruptured at discrete locations on the metal surface will create an initiating site for corrosion to occur. Initially the oxide covered surface is much less chemically active than a bare or unlimited surface, and it will be the cathode in an electrolyte.

The anodes may be located at discontinuities in the oxide film covering the metal surface. They may be located at a grain

boundary where a mismatch of metal lattices is large, or they may result from inhomogeneous composition of the metal at an area on the surface.

The latest theories of the mechanisms of stress corrosion cracking, a film-rupture mechanism, is that stresses applied from fabrication processes, i.e., punching, rolling, spinning, welding, etc., will rupture this oxide film on the metal surface. The film-free surfaces are normal to the applied stress and very narrow compared to the film-covered surfaces separating them. A film-free surface may be 0.15 Volt or more anodic to a film-covered surface. Metal ions will be dissolved at those anodes, corrosion current will flow to the cathodes, and hydrogen will be discharge there.

Both anodes are very small compared to the cathodic area, the current density will be large at the anodes and trenches or grooves will be formed. These grooves concentrate the stresses at the groove tips, preventing the film from reforming there. Because effective stresses soon disappear on the sides of the groove, a film will form there and thus produce cathode areas very close to the anodes to accelerate the corrosion cell activity.

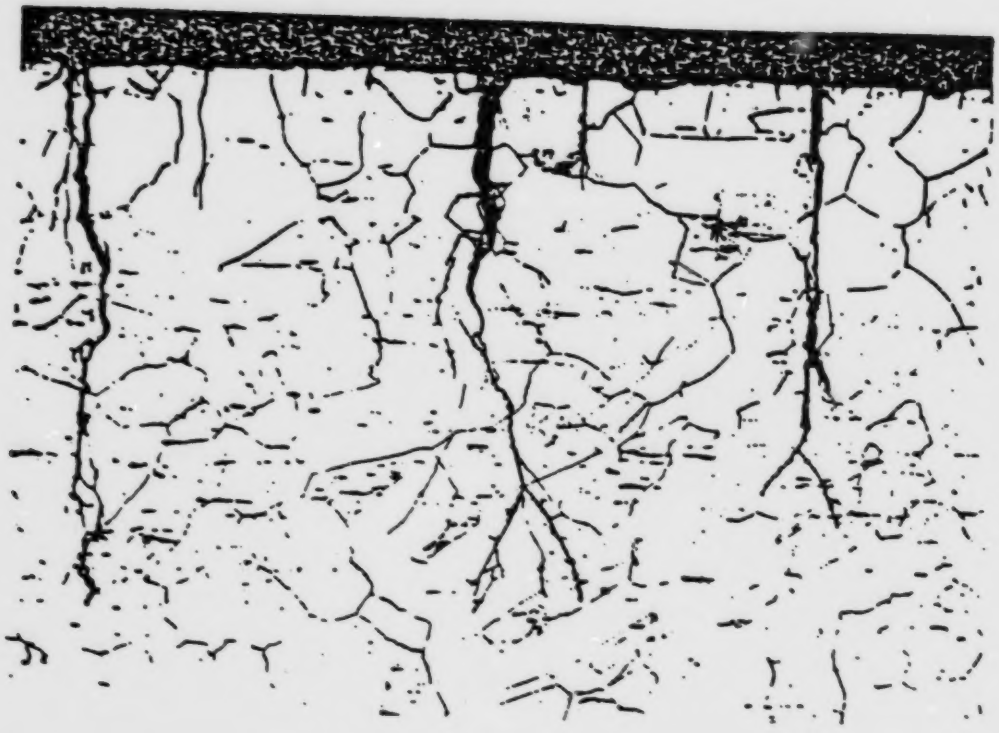


Figure 9. Transcrystalline stress corrosion cracking (SCC) in a type 304 austenitic stainless steel. X 100. Chloride attack. (Courtesy Uganski and Stiefel, National Bureau of Standards.)

Figure 10. Intergranular stress corrosion cracking (SCC) in a type 304 austenitic stainless steel by oxygenated high purity water. X 500.

Two types of stress corrosion cracking, namely:

Transgranular chloride attack shown in Figure 9, (6)

Intergranular oxygen carbide percipitated attack shown in Figure 10, (7)

represent the most probable corrosion failure mechanism for stainless steel in solar heated water service.

Corrosion Kinetics

Corrosion Current

Corrosion cells, having been established by one or more of the mechanisms discussed in the previous section, need not result in serious corrosion damage whether or not corrosion is a serious problem depends principally on the rate of corrosion or corrosion kinetics. Thus the corrosion rate is determined by the rate of the oxidation reaction at the anode site and the corresponding reduction reaction rate at the cathode site. These rates are difficult to measure directly but a by-product of these reactions, namely, charge transfer, can be measured. The rate of charge transfer (corrosion current) will be a direct representation of the rate of the corrosion reaction.

As previously discussed, the corrosion weight loss at the anode of a corrosion cell is proportional to the charge transfer between the anode and cathode. It follows then that the consumption rate (weight loss per unit time) is proportional to the corrosion current where:

$$W = \frac{MQ}{Fn} \quad (3)$$

But since $$I = \frac{Q}{t} \quad (8)$$

Then $Q = It$ which when substituted in (3)

Gives $$W = \frac{MIt}{Fn}$$

Therefore $$\frac{W}{t} = \frac{MI}{Fn} \quad (9)$$

Electrical Model of Corrosion Cell

Any corrosion cell can be modelled by a simple electrical circuit. Consider the following localized corrosion cell in Figure 11. As there is a charge accumulation at both anode and cathode sites initially, then each site can be considered a small battery, albeit with a different charge density, and therefore a different electro-motive force (EMF). Located between these two EMF's is the electrolyte resistance and the metal resistance.

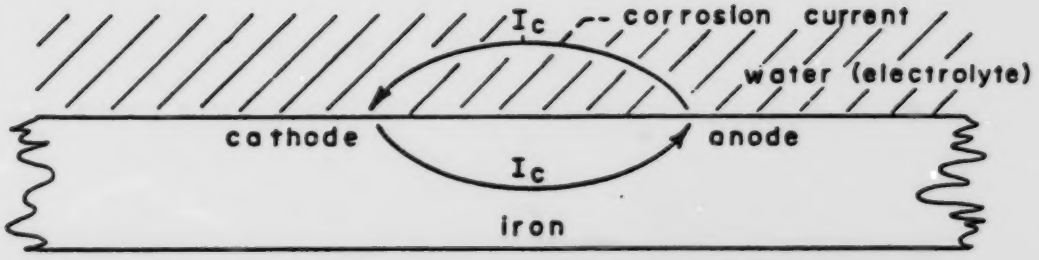


Figure 11. Simple corrosion cell.

The following simple circuit is therefore an electrical model of this electro-chemical corrosion cell.

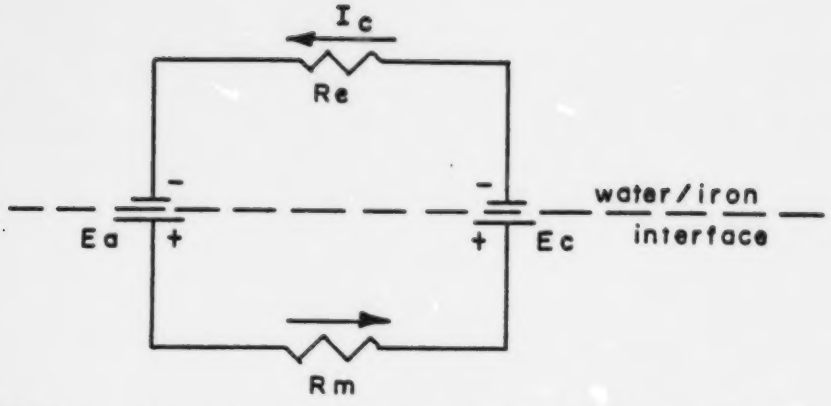


Figure 12. Simple electrical circuit model of a corrosion cell.

In the diagram, Ea and Ec are the solution potentials of the anode and cathode respectively. Note that these EMF's oppose each other so that the net EMF or corrosion potential difference is in effect the potential difference between the anode and cathode. The resistors Re and Rm represent the resistance to current flow in the water electrolyte and iron or metal paths respectively. The current in this circuit is given by:

$$Ic = \frac{Ea - Ec}{Re + Rm} \quad (10)$$

Reference(10) indicates that the corrosion current (Ic) depends directly on the magnitude of potential difference between the anode and cathode and inversely on the circuit resistance. It follows then that the magnitude of corrosion or the rate of the corrosion reaction is also a function of these two parameters.

Electrolyte Electrical Resistivity

In most corrosion cells the electrolyte path resistance is very much greater than the metal path resistance. The corrosion consumption rate at the anode is therefore controlled predominantly by electrolyte path resistance. When the electrolyte electrical resistance is small, the corrosion current and consumption rate will be correspondingly high as illustrated in Figure 13.

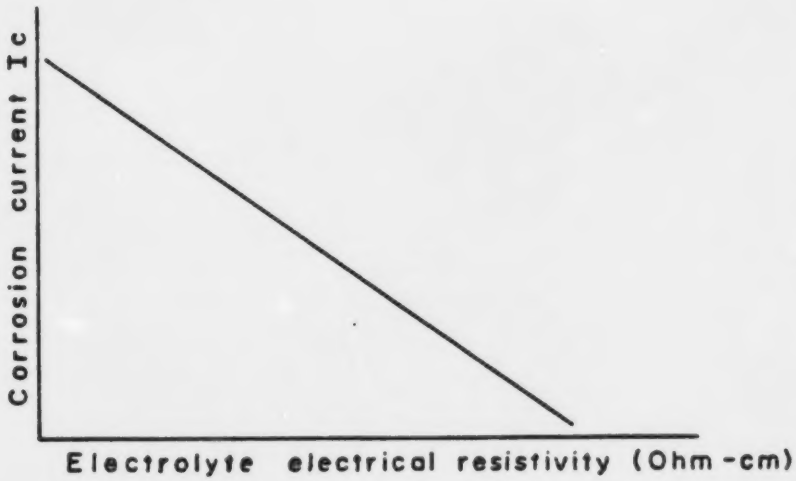


Figure 13. Relationship between corrosion current (consumption rate and electrical resistivity of the electrolyte.

The reciprocal of electrical resistance is conductance. Divide conductance in micromos per centimetre by one million to change it to resistivity in ohm-cm.

For example: 770 micromos per centimetre conductance

$$\frac{1,000,000}{770}$$

Equals 1,299 ohms cm. resistance

Electrical Resistivity Factors

Electrical resistivity is a property which is specific to the particular substance or solution and therefore called the specific resistance. The total circuit resistance in a corrosion cell between the anode and the cathode sites is the sum of the resistance of both the metallic as well as the electrolytic current paths. In most corrosion cells the metallic path resistance is small compared to the electrolyte path resistance, which therefore dominates the circuit resistance and essentially controls the corrosion current flow. The resistance (R) of either the metallic or electrolytic path is a function of the material resistivity (p) and the path geometry as given in the following relationship.

$$R = \frac{pL}{A} \quad (11)$$

Where p = electrical resistivity (ohm-cm.)

L = path length (cm.)

A = cross-sectional area of current path (cm^2)

The electrical resistivity of solar heated potable water depends on several factors, two which are considered important in this study are the amount of chloride and the water temperature.

Potential Difference Between Anode and Cathode

It follows from Reference (10) that the corrosion current, and therefore the corrosion rate, is also dependent on the magnitude of potential difference between the anode and cathode sites in the corrosion cell. Referring to the galvanic series of Table 2,

it can be seen that the potential difference between steel and copper could be as much as 0.6 Volt and between zinc and copper is 0.9 Volt. The relationship between corrosion cell potential difference and corrosion rate is illustrated in Figure 14.

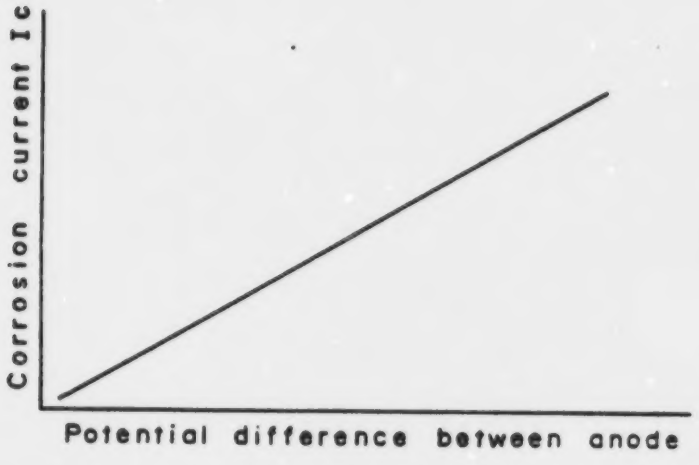


Figure 14. Relationship between corrosion current (consumption rate and the potential difference between anode and cathode.

In general, the potential difference between anode and cathode sites on the same metal are usually small in comparison to those in corrosion cells composed of different metals. Accordingly, where all other factors are constant, the greater the potential difference, the greater will be the corrosion rate. Galvanic or internally generated potential differences are often large compared to externally applied concentration differences from the solar heated potable water. This explains the fact that corrosion arising from connecting an iron tank into a completely copper residential or commercial water piping system is often more severe

than the aggressiveness of the water supply.

Anode/Cathode Areas

As stated earlier, the kinetics or rate of the corrosion reaction depends directly on the rate of the interdependent oxidation and reduction reactions occurring simultaneously within the corrosion cell. These reaction rates can only be gauged by the cell corrosion current which in turn relates to the consumption rate at the anode site.

In determining the severity of corrosion, however, the consumption rate may not be as important as the corrosion rate. For example, the weight loss of one kilogram of metal per year taken evenly off the entire surface area of the solar tank wall may not be considered too important. If, however, one kilogram of metal were removed from a few square metres of the tank wall it could be perforated in a few months. An additional important parameter, therefore, is the corrosion current density.

From Reference (9) it was given that:

$$\frac{W}{t} = \frac{MIc}{Fm}$$

Dividing this equation by the surface area (Aa) of the anode gives:

$$\frac{W}{tAa} = \frac{MIc}{FnAa}$$

But $\frac{Ic}{Aa}$ = ic (corrosion current density at the anode)

Therefore $\frac{W}{tAa} = \frac{MiC}{Fn}$ (12)

Hence, the weight loss per unit time per unit area (corrosion rate) is proportional to the corrosion current density at the anode site.

The surface area of the anode site becomes an important factor in determining the severity of corrosion. Further, there is interdependence between the anode and cathode surface areas and the corrosion rate as illustrated in Figure 15.

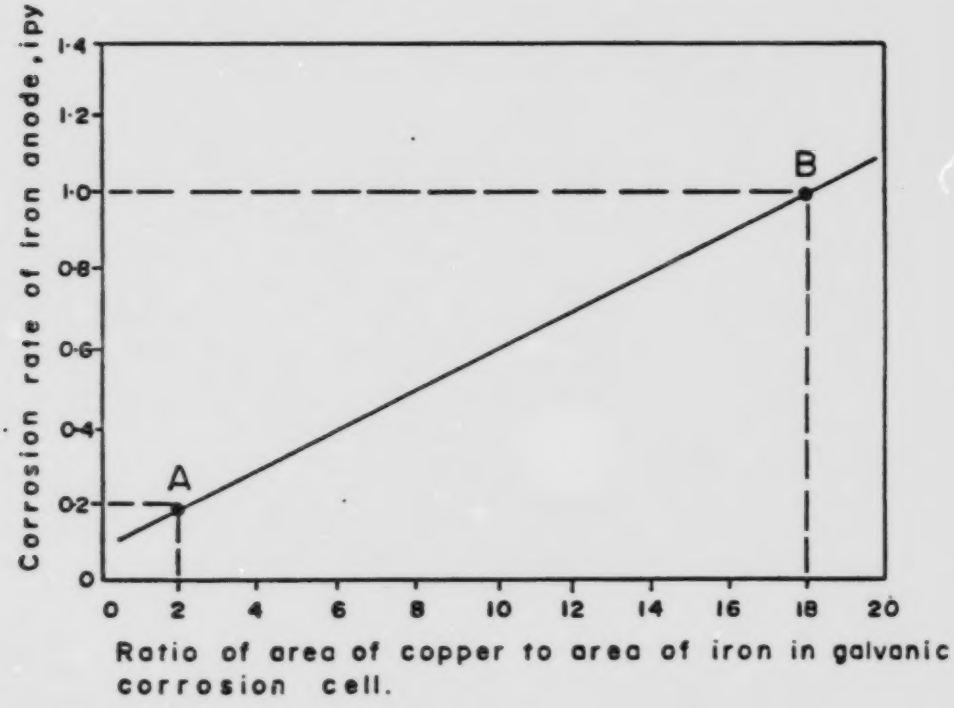


Figure 15. Corrosion rate as a function of copper/iron area ratio in sea water. (11).

The foregoing curve was produced by immersing copper cathodes and steel anodes of various surface ratios in a sea water environment.

to the anode via the external electrical path. The weight loss from an anode is related to the magnitude of this cell current.

Corrosion cells may be internally driven (galvanic) due to anode and cathode of different metals in a homogeneous environment or anode and cathode in different environments. They may also be corrosion cells externally driven by concentration differences in the solar heated water. An example of a galvanic cell involving different metals is the selection of a steel tank connected to an extensive copper water system. A steel tank in the direct active draindown (open loop) solar hot water system type can corrode due to the difference between the top and bottom aqueous environments resulting from the greater amount of oxygen in the aerated environment nearest the top of the tank. Concentration differences in the aqueous environment can cause corrosion where the natural protective film is disturbed or ruptured at discrete locations on the metal surface. The solar water resistivity, its hardness or ability to form calcium deposits will play an important role and in the case of stainless steel chloride, oxygen levels, and temperature may cause stress corrosion cracking.

The existence of a corrosion cell does not necessarily result in serious damage since several factors can limit the corrosion current. Specifically, high water resistivities tend to reduce currents and damage as does the involvement of anodes and cathodes between which there are only modest electrical potential differences.

corrosion cell activity a place to start its destructive operation as illustrated in Figure 16.

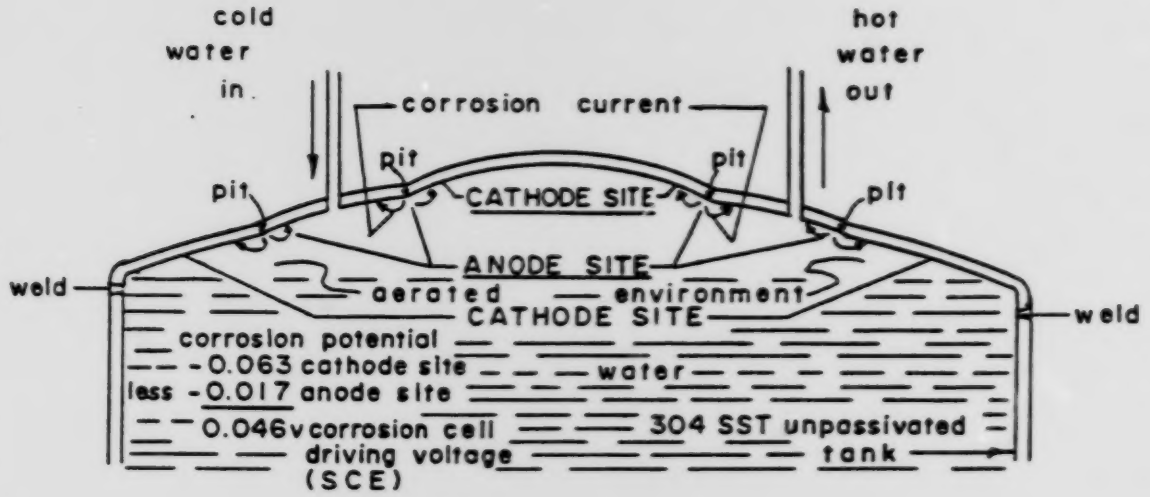


Figure 16. Corrosion pitting of unpassivated type 304 stainless steel.

Summary

Corrosion of metal is an oxidation process whereby positively charged ions leave the metal and enter the electrolyte. Different metals have different tendencies to corrode, the most active being those with the most negative electrical potential when in an aqueous environment. All corrosion cells have (a) an anode, (b) a cathode, (c) an electrolyte in which both the anode and cathode are situated and (d) an external electrical path between the anode and cathode. In this cell the anode corrodes causing the current to flow in the electrolyte to the cathode, returning

Assuming operating Point A and B are situations where the total corrosion current Ic is the same, then the larger difference in corrosion rate is entirely due to the difference in anode/cathode surface areas. Position A might be comparable to a steel tank interconnected to a minimum amount of copper piping. Since the area of the copper that can become active in a corrosion cell is small and the steel tank area relative to the copper cathode area is large the corrosion rate on the tank is low. Conversely, Position B, where the corrosion rate of the steel is high, would be comparable to an extensive copper piping system (large cathode) connected to a steel tank (small anode). In both cases the same potential difference is present, and the same corrosion current could flow, but the difference in severity of the corrosion damage is entirely due to the surface area relationship between the anode and cathode.

Corrosion pitting resulting in a greatly shortened tank life was reported during this study on an unpassivated type 304 stainless steel tank from Richmond, British Columbia. The pitting was located exclusively in the top of the tank at discrete locations where the natural protective film was ruptured by the mandrel during the cold work metal forming operation in the manufacture of the top hub of the tank. Since the tank did not receive any beneficial passivating treatment small anodic sites formed in the highly oxygenated electrolytic environment. The small anodic site compared to the large cathodic site adjacent to it allows

Furthermore, galvanic cells in which the anode area is large in comparison to the cathode area will result in less damage than if the reverse were true.

Corrosion Prevention

Methods of Corrosion Control

Recognizing that the loss in Gibb's Free Energy when a metallic element is transformed to its corrosion product is the fundamental cause of corrosion in an aqueous environment suggests material selection as one method of corrosion control. Accordingly, one can use a more noble material (e.g., one with less loss of Gibb's Free Energy) to obtain better corrosion resistance. This is only one of many proven techniques for corrosion mitigation which are listed below:

- material selection
- material passivation
- environmental control
- instal ion trap filters
- inhibitors
- protective coating
- electrochemical protection
    - cathodic protection

Of the above methods only material selection and passivation are a controlable cost from a tank manufacturer's point of view. All other methods are applicable as an additional cost item. The

suitability and merit of the methods vary with the generic type of solar system found in Appendix "A" and environmental differences in the solar heated water.

Material Selection

Material selection is not limited to a choice of either a more noble metal or a non-metallic material. State of the art for non-metallic materials for solar heated water tanks is that they are not acceptable. Some materials such as carbon steel, when alloyed with other metals such as chromium, nickel and molybdenum, are imported with a passive film which provides the metal alloy with a relatively impermeable oxide barrier. These materials, such as stainless steels, have much improved corrosion resistance compared to the parent metal. The increased cost for stainless steel is justified in view of the long term, maintenance free operating life, of solar hot water systems.

The principal material selection decisions are focused on the tank and since there are a variety of types ranging from stainless steel, copper and carbon or mild steel. In general, it is good corrosion control practice to consider the surface area ratio of different metals in relation to the other metals in the total solar system. When circumstances preclude the use of a common metal approach, one should make sure that the anode material surface area in a mixed metal network far exceeds the surface area of all cathodic metals. For instance, serious dissimilar

metal corrosion of a mild steel tank will occur unless additional measures are taken such as coating and cathodic protection.

Material selection, however, is often a practical approach to corrosion control. For example, a copper tank is subject to disruption of its oxide film easily and pitting corrosion leads to an unacceptably short tank life in most cases.

The materials to be considered can be found in the mill test report showing the metal element composition in Appendix "C" of this report. A list describing the corrosion resistance for stainless steels obtained from manufacturers' technical data is located in Appendix "C" of this report. (13), (14)

Material Passivation

It has been said earlier under Corrosion Fundamentals that anything which causes the natural metal oxide film to be disturbed or ruptured will create a discrete location for corrosion cell activity. Passivating treatment removes surface contamination at these locations. Passivating a stainless steel tank is a corrosion control measure designed to remove discrete location sites and therefore assists forming the desired protective film.

Environmental Control

Achieving the objectives of this investigation requires an understanding of several measurable water chemical and physical

analysis parameters. Taken individually each parameter will not in itself be conclusive but collectively all parameters will assist in giving a reasonably accurate assessment of what corrosion cell activity can be expected by any metal in any aqueous environment.

The chemical and physical analysis parameters considered applicable for potable water in a solar tank are listed below:

General mineral

- Oxygen content (aerated water)
- Carbon dioxide CO_2
- Chlorides
- pH
- Alkalinity
- Hardness, calcium carbonate, $CaCO_3$
- Resistivity/Conductivity

General physical

- Temperature
- Flow (turbidity)
- Aggressiveness index
- Langelier saturation index
- Ryznar stability index

Oxygen Content

Water normally contains a few parts per million of oxygen which has a major influence in combination with chlorides on suscept-

ability to stress corrosion cracking. Solubility of oxygen in 80 degrees C (175 degrees F) is about 3 parts per million. Solubility is higher at lower temperatures. At the boiling point, the solubility is, of course, nil. Boiled water that is not afterwards strongly mixed with air (by agitation, falling through air, etc.) will be less corrosive, and thus, this factor need be taken into account.

The temperature variation for solar heated water is taken to mean from below freezing on the low end of the scale to flashing water into steam 100 C (212 F) on the high end of the scale. (15).

On the basis of oxygen content water, stored in the seven generic types of solar systems found in Appendix "A", would be listed in order of corrosion cell activity as follows:

SOLAR SYSTEM TYPE, CORROSION ACTIVITY LIST

Corrosion Cell Activity	Solar Generic Type	Solar Water System Type	Reference Appendix "A"
Open Loop 1	2	Direct Active Draindown	Figure 3, No. 2
Open Loop 2	1	Direct Active Recirculation	Figure 3, No. 1
Open Loop 3	4	Direct Passive Internal Collector/Storage	Figure 4, No. 4
Open Loop 4	3	Direct Passive Thermosyphon	Figure 4, No. 3
Closed Loop 5	5	Indirect active drainback	Figure 5, No. 5

Closed Loop 6	6	Indirect active heat exchanger Figure 5, No. 6
Closed Loop 7	7	Indirect Passive Thermosyphon Figure 6, No. 7

Corrosion cell activity No. 5, 6, and 7, for closed loop systems see Corrosion Prevention, Inhibitor Section, of this report.

Carbon Dioxide CO_2

It has been explained earlier that when a natural water is capable of forming a scale it is beneficial in reducing corrosion cell activity. Carbon dioxide in more alkaline waters reacts with constituents to form bicarbonates or carbonates to form hardwater scale. In acid water the carbon dioxide is dissolved in the water and can easily come out as so called free CO_2 since it is not combined to form bicarbonates or carbonates. If much free CO_2 is present in the water it promotes corrosion. Water temperature will also affect the scale formation process. Higher temperature promotes more scale and lower temperature promotes less scale. (16)

Chlorides

Chlorides will concentrate at crevices, and in weld scale, weld oxides, etc. They will also concentrate through evaporation. Thus no absolute limits can be given. The following chloride maximums can be considered as practical limits for water with pH 6.0 to 9.0:

304L	25 ppm.	Cl^- Max.
316L	100 ppm.	Cl^- Max.
FAL223	5000 ppm.	Cl^- Max.

The austenitic stainless steels, 304L and 316L could fail due to chlorides above these limits by stress corrosion cracking or pitting/crevice corrosion. The martensitic 400 series could fail only by pitting/crevice corrosion. These limits can be adjusted slightly up or down depending on the practical pH. The higher the pH, more alkaline is better and oxygen content the lower is better. (17)

304 stainless steel is subject to stress corrosion transgranular cracking in water containing chlorides at two percent by volume. (18)

316 stainless steel is more resistant to crevice corrosion, reducing acids and contact corrosion, in water containing chlorides. (19)

400 series stainless steels are known to have hydrogen induced cracks. (19)

444 series stainless steels have achieved several years of successful operating experience and is standard for virtually all solar collector service in Japan. (14)

pH

p stands for power and H stands for hydrogen. pH is the power of

ten needed to express the hydrogen ion concentration in moles per litre. A neutral solution is pH of 7. An acid solution is less than pH of 7. A basic solution is greater than pH of 7. The pH value of water is one of several indicators useful in determining the relative corrosiveness to a particular metal.

Alkalinity

Alkalinity is a substance as in a carbonate of calcium that has marked basic properties. High alkalinity is considered to be over 100 parts per million.[20] Corrosion pitting diminishes with increase of alkalinity.

Hardness $CaCO_3$

Water high in the mineral salt calcium carbonate is considered to be hard water. Hard water will deposit scale when heated.

Resistivity/Conductivity

People in the corrosion engineering field use resistivity and people in the waterworks industry use the reciprocal conductivity. Resistivity is used to predict the probable corrosiveness of the electrolyte (water).

Table 7 - Rough Indications of Water Corrosivity Versus Resistivity

	Ohm-Cm.	Description
Sea Water	30	Very Corrosive
Potable Water		
- San Diego, Ca.	1,300	Corrosive
- Vancouver, B.C.	29,000	
Demineralized Water	100,000	Progressively Less Corrosive

Temperature

As stated earlier under carbon dioxide and hardness increased pitting rate coincides with increased temperature.

Flow (Turbidity)

Corrosion pitting is less pronounced in rapidly moving aerated solutions, compared to stagnant solutions.

In excess of five decades the literature shows work has been done to try and simplify one way to measure the corrosiveness of water. As in the case of the Medieval Alchemists no one has been able to find one answer. There are three indexes in use today, namely:

Aggressiveness Index (1980)

Langelier Saturation Index (1936)

Ryznar Stability Index (1944)

All three indexes are an attempt to rank the corrosiveness of water by taking into account the ability to lay down a protective film and all use oxygen content, carbon dioxide, pH, alkalinity, hardness and temperature in one form or another. The writer's choice is the Aggressiveness Index because of its simplicity. However, the next most popular is the Langelier Saturation Index and finally the Ryznar Stability Index are all outlined because they are usually shown in physical analysis of water samples.

Aggressiveness Index (21)

The Aggressiveness Index is simply a measure of the water corrosiveness in its natural state with no inhibitors. It is a simplification of the Langelier Saturation Index. In developing this index Millette and others obtained water samples from 130 utilities serving 40 million people, approximately one-fifth of the United States population. More than 1300 water samples were tested from 35 geographic locations. The results show almost 70 percent of the representative utilities have moderately to highly aggressive water. Two-thirds of the utilities representative of United States water supplies had what is considered aggressive water by A.W.W.A. C400-77 standard.

The aggressiveness of water is defined in the forward to the

A.W.W.A. standard for asbestos-cement distribution pipe as:

1. Highly Aggressive: pH + log (AH) less than or equal to 10.0
2. Moderately Aggressive: pH + log (AH) equals 10.0 to 11.9
3. Non-Aggressive: pH + log (AH) more than or equal to 12.0

Where A = total alkalinity in mg/L $CaCO_3$

H = calcium hardness as mg/L $CaCO_3$

According to Standard C400, it is recognized that water with a pH + Log_{10} (AH) less than or equal to 10 is extremely aggressive and would be very corrosive to almost all materials found in a typical water system, including plumbing in consumers' homes.

A comparison of the average aggressiveness indexes of utility waters from representative areas in the United States is as follows:

Highly Aggressive	16.5 percent
Moderately Aggressive	52.0 percent
Non-Aggressive	31.5 percent

A survey of literature by Merrill and Sanks[22] suggests that the characteristics of a well-conditioned (oversaturated) water include the following:

1. An oversaturation of $CaCO_3$, with a $CaCO_3$ precipitation potential of 4 to 10 mg/L.
2. Calcium and alkalinity values of at least 40 mg/L as $CaCO_3$, with calcium and alkalinity present in approximately equal concentrations.

Millette states 55 percent of utilities surveyed met Condition 2 above.

3. An alkalinity to (Cl^- + SO_4^{-2}) ratio of at least 5:1 with all concentrations expressed as $CaCO_3$.
4. pH in the range of 6.8 to 7.3. The pH range 8.0 to 8.5 has less ability to absorb excess acid and base caused by the corrosive process. Outside this range the water's absorption or neutralizing ability is better and it is more protective, meaning passivating properties of the protective oxide films is enhanced.

Millette states 10.5 percent of utilities surveyed have pHs in the range 6.8 to 7.3 and 14 percent of the utilities have pHs in the range 8.0 to 8.5.

Langelier Saturation Index (23), (24)

The Langelier Saturation Index is a measure of the degree of calcium carbonate saturation in water. It has been used extensively in estimating the corrosion potential of water. The basic equations are as follows:

Saturation index = pH actual -pH saturation

pH saturation = $(pK'_2 - pK's) + pCa^{++} + pALK + S$

Where $(pK'_2 - pK's)$ = Dissociation constant estimates based on temperature and total dissolved solids or ionic strength.

pCa^{++} = -log (Calcium in moles per litre)

pALK = -log (Total alkalinity in equivalents of $CaCO_3$ per litre).

S = Salinity correction term equals $2.5\ u^{\frac{1}{2}}/(1 + 5.3\ u^{\frac{1}{2}} + 5.5\ u)$

u = ionic strength

- To convert specific conductance (in u S/cm) Micro Siemen equivalent equals 0.9 mg/L dissolved solids.
- Total dissolved solids contents less than 500 mg/L, the ionic strength may be estimated by 2.5×10^{-5} x the total dissolved solids.
- An alternate approximation of ionic strength can be made using total hardness and total alkalinity.

If the index is zero, the water is in equilibrium.

If the index is positive, the water is oversaturated meaning a tendency to lay down a protective film.

If the index is negative, the water is under saturated meaning a tendency to be aggressive.

The greater the negative value the greater the aggressiveness.

Ryznar Stability Index

The Ryznar Stability Index is a quantitative index of the amount of calcium carbonate scale that would be formed and to predict the corrosiveness of waters that are nonscale-forming. The

stability index uses the same parameters as the Langelier Saturation Index. The basic equations are as follows:

RI = 2pH saturation - pH actual

OR

RI = pH actual - 2LSI

Where pH actual and pH saturation are as defined in the Langelier Saturation Index (LSI).

If the index is zero, the water is non aggressive.
If the index is six (6), or less causes scale.
If the index is seven (7), or more, it causes corrosion.
If the index is eight point five (8.5) corrosion is moderately aggressive.
If the index is ten (10), or more, the water is highly aggressive.

Table 8 - Summary of Corrosivity of Waters Using Three Indexes

	Aggressiveness		
	Highly	Moderately	Non
Aggressiveness Index	Less Than	10 to 11.9	12 or more
Langelier Index	Negative	Positive Value	Zero
Ryznar Index	10 or More	7 or More	Zero

Environmental Control - Instal Ion Trap Filters

Components added to the solar system will minimize corrosion by removing deposits which can contribute to disruption of the natural protective oxide film and create a discrete location

where corrosion activity has a place to get started.

Sedimentary filters are the first obvious type which will remove small particles and scale from the solar heated water.

Another type of filter suggested by Thompson and Hayden is termed a "getter column". The column serves two purposes, firstly, as a fine filter and secondly, as a chamber that contains electrochemically active sacrificial anode material in the form of replaceable zinc or magnesium wool pads. It provides some corrosion protection to the steel, copper and brass which may be in the piping system. The getter column or ion trap is a good practical way to visually indicate the rate of corrosion activity by observing the condition of the last wool pad.

Inhibitors

Inhibitors cannot be considered for open loop solar hot water system types because it would be too expensive and the danger of a health hazard by contaminating potable water supplies.

Inhibitors are a viable corrosion prevention measure for closed loop solar hot water system Types 5, 6. Reference Appendix "A", Figure 2 and 5. Inhibitors for a specific water supply are available. Consult your local inhibitor specialist.

Inhibitors are necessary where antifreeze is used and are

for the ability of water to lay down a beneficial protective film on the metal. Various other extra components such as filters and inhibitors have merit.

Protective coatings can be effective in preventing corrosion, however, only glass-lined tanks have been proven successful over a fifteen-year life and only then when electrically insulated from copper piping and cathodically protected.

Selecting appropriate metals to avoid corrosion might include the use of noble metals or special alloys such as stainless steel. The increased cost is justified considering net solar economic return on the investment. It is of great significance to select materials which have the least difference in Gib's free energy loss such that there is not a mixture of different metals electrically interconnected. When more than one metal must be used, corrosion problems will be minimized if the surface area of the anode (least noble) metal far exceeds the cathode area. Copper tanks are not acceptable for reasons given. Several types of stainless steels are available each having increasing basic costs coinciding with increased corrosion resistance. Selecting the correct type of stainless steel depends to a large extent on the water environment.

Environmental control of the aqueous electrolyte is intricately involved with material selection. One can change the metal but one has little control over the water in the tank. Corrosivity of water is decided by collectively analysing several chemical and physical parameters. Oxygenated water is more corrosive than stagnant. Chlorides cause stress corrosion cracking, pitting and crevice corrosion of stainless steel. Resistivity determines the corrosion current that will flow. Increased temperature coincides with increased corrosion. The aggressiveness of water involves oxygen, carbon dioxide, pH, alkalinity, hardness and temperature. All are very important in accounting

piping system. The cost efficiency of cathodic protection is dependent upon a good coating for anode life expectancy considerations. It can be seen from the above that except in the case of a glass-lined tank coating is impractical. The reason glass-lined tanks achieve a fifteen-year life is because the poorly coated area inside a tank where the coating application nozzle exits the tank is small.

The second important principle of cathodic protection which must be achieved is the installation of a di-electric insulating union at all inlet and outlet connections between the steel tank and the copper piping. This electrical insulator prevents the flow of corrosion current in the corrosion cell between the steel tank and the copper piping.

It should be pointed out that in most cases coating, cathodic protection and electrical insulation are an essential combination in order to achieve fifteen-year life of a steel tank in a copper piping system.

Summary

Corrosion prevention requires that the metal or the water be made less active by methods such as:

- Material selection
- Environmental control
- Protective coating
- Electrochemical protection

unnecessary in solar hot water types where air, freon or oil are used. Reference Appendix "A", Figure 2.

Protective Coating

While there are two or more coating suppliers of polyurethane material whose technical data claims an operating temperature of 98° C (-200° F) to 176° C (350° F) the writer is very doubtful that the coating would withstand hot water service for five years or ten years let alone 15 years minimum. The writer tends to agree with Headon who states that ten years in hot water is rather severe. He also states that glass-lined tanks have a life of at least 15 years in Ontario waters. Stone-lined tanks or concrete-lined tanks have never had a corrosion failure but they weight 50 percent more than glass-lined tanks.

Tanks with the metallic coating, heavy duty galvanizing in 1948 at Windsor, Ontario, showed 65 tanks out of 450 developed leaks in the first year.

It can be demonstrated from the above that protective coating is not considered a viable alternative corrosion prevention measure.

Electrochemical Protection - Cathodic Protection

Cathodic protection is a technique whereby the anode is made the cathode in a corrosion cell. It is accomplished by installation of a zinc or magnesium anode attached to a steel tank in a copper

Chemex Labs Ltd.

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• Analytical Chemists • Geochemists • Registered Assayers

Phone: (604) 984-0221
Telex: 043-525!

CERTIFICATE OF ANALYSIS

TO : LEMON, MR. D.W. & ASSOC. LIMITED
ATTN: D.W. LEMON
14435 CHARTWELL DRIVE
SURREY, BC

CERT. # : W 4482

ATTN: MR. D.W. LEMON

Sample description	INITIAL WEIGHT (GRAMS)	FINAL WEIGHT GRAMS
304 1&2	54.4161	54.4069
3&4	55.5499	55.5415
304L 1&2	51.5412	51.5247
3&4	51.7680	51.7619
316 1&2	50.7760	50.7756
3&4	51.4945	51.4903
316L 1&2	50.0953	50.0697
3&4	50.6051	50.5890
444 1&2	60.1618	60.1575
3&4	60.1198	60.1164
110 & 122 1	60.2550	60.2118
110 & 122 2	58.3017	58.1482
110 & 122 3	60.5342	60.4716
MILD STEEL 4140 1&2	51.2652	49.6740
MILD STEEL 4140 3&4	51.6858	50.4008
MILD STEEL 4140 5&6	51.0413	50.4243

V01 REV 3 80

Certified by .....

ANNUAL SHIPMENTS BY LOCATION OF COMPANY HEADQUARTERS[a]
(Thousand Square Feet)

Location[b]	1984	1983	1982	1981
Alabama	183	130	223	126
Arizona	767	890	858	730
California	5,725	6,579	6,076	10,544
Colorado	818	718	1,019	487
Connecticut	200	W	35	93
Florida	3,093	2,886	3,876	1,652
Georgia	W	25	27	72
Hawaii	104	19	26	W
Illinois	17	82	32	142
Indiana	39	W	W	W
Iowa	208	93	57	26
Kansas	0	W	W	14
Maine	45	W	W	W
Maryland	0	W	W	W
Massachusetts	49	W	163	141
Michigan	480	W	65	28
Minnesota	35	W	302	111
New Hampshire	38	W	27	W
New Jersey	640	691	1,139	1,902
New Mexico	340	W	583	W
New York	1,454	1,968	1,670	2,036
North Carolina	50	W	250	12
Ohio	680	252	104	251
Oregon	92	65	83	W
Pennsylvania	94	W	174	271
South Carolina	W	W	20	15
Tennessee	W	155	365	167
Texas	476	W	421	535
Virginia	368	W	383	309
Wisconsin	9	W	28	38
Other[c]	415	2,276	616	431
U.S. Total[d]	16,419	16,828	18,621	20,133

[a]Includes adjusted data for nonrespondents.
[b]Location refers to the address of company headquarters which is not necessarily the location of the manufacturing installation.
[c]Total for States having less than three respondents.
[d]Sum of components may not equal total due to independent rounding.
W = Value withheld to avoid disclosure of company data.

SOURCE: Energy Information Administration, Solar Collector Manufacturing Activity.

DEAR CUSTOMER:

HERE IS THE MILL TEST REPORT FOR THE MATERIAL ON YOUR PURCHASE ORDER 076. THIS TEST REPORT IS CORRECT TO THE BEST OF OUR KNOWLEDGE.

THANK YOU

GARY E. LEDBETTER
QUALITY CONTROL MANAGER

ALLOY: 316 HEAT: D370 MILL: EASTERN STAINLESS

ELEMENTS: C-.050: Mn-1.47: P-.023: S-.025: Si-.60: Cr-17.75: Ni-10.68: Cu-.20:
ELEMENTS: Mo-2.05: Co-.23: N-.058

TENSILE STR.: 94.9 ksi
ELONG.: 46.0 %
HARDNESS: BHN 87

YIELD PT: 52.3 ksi
RED. OF AREA: na

ALLOY: 316L HEAT: 800 MILL: ALLEGHENY LUDLUM

ELEMENTS: C-.020: Mn-1.71: P-.035: S-.002: Si-.60: Cr-17.01: Ni-11.08:
ELEMENTS: Mo-2.12: N-.03

TENSILE STR.: 85.5 ksi
ELONG.: 58 %
HARDNESS: Rb 77

YIELD PT: 43.0 ksi
RED. OF AREA: na

ALLOY: 304L HEAT: D489 MILL: ARMCO

ELEMENTS: C-.020: Mn-1.39: P-.022: S-.015: Si-.54: Cr-18.27: Ni-9.44: Cu-.47:
ELEMENTS: Mo-.10: Co-.18: N-.023

TENSILE STR.: 81.9 ksi
ELONG.: 59.0 %
HARDNESS: na

YIELD PT: 38.9 ksi
RED. OF AREA: na

ALLOY: 304 HEAT: D490 MILL: WASHINGTON STEEL

ELEMENTS: C-.060: Mn-1.34: P-.029: S-.011: Si-.61: Cr-18.08: Ni-8.33: Cu-.32:
ELEMENTS: Co-.20: N-.08: Mo-.28

TENSILE STR.: 90.5 ksi
ELONG.: 56.0 %
HARDNESS: 45T/53.5

YIELD PT: 46.7 ksi
RED. OF AREA: na

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BRITISH COLUMBIA, CANADA V7J-2C1

PHONE (604) 984-0221

CERTIFICATE OF ANALYSIS A8711698

To: LEMON, MR. D.W. & ASSOC. LIMITED
ATTN: D. W. LEMON
14435 CHARTWELL DRIVE
SURREY, B.C.
V3S 5E3

Page No. : 1
Tot. Pages: 1
Date : 27-FEB-87
Invoice # : I-8711698
P.O. # : NONE

Project :
Comments:

PARAMETER DESCRIPTIONS	SAMPLE CALIFORNIA	SAMPLE NEVADA	SAMPLE NEW YORK	SAMPLE FLORIDA	SAMPLE WINDSOR	SAMPLE GEORGIA	SAMPLE TEXAS	SAMPLE VANCOUVER		
Sample preparation code	221	221	221	221	221	221	221	221	---	---
Sample preparation code	---	---	---	---	---	---	---	---	---	---
pH	8.0	7.2	6.5	6.6	6.5	6.4	7.3	5.9		
Alkalinity (mg/L CaCO3)	120.0	133.0	98.0	79.0	87.0	65.0	201	5.0		
Conductivity (umhos/cm)	830	905	480	190	290	145	575	35		
Tot Hardness(mg/L CaCO3)	232	275	177.0	109.0	134.0	69.0	134.0	13.0		
Chloride (ppm)	49.0	49.0	40.0	42.0	11.0	1.0	11.0	0.9		

CERTIFICATION : _____

ALLOY: 444 (18-2) HEAT: E423 MILL: ALLEGHENY-LUDLUM

ELEMENTS: C-.018: Mn-.40: P-.023: S-.002: Si-.28: Cr-18.02: Ni-.34: Mo-1.95:
ELEMENTS: Cu-.14: Ti-.17: N-.034: Cb-.33: V-.12

TENSILE STR.: na YIELD PT: na
ELONG.: na RED. OF AREA: na
HARDNESS: na

ALLOY: CDA 110 HEAT: E457 MILL: na

ELEMENTS: Cu-99.90 min
ELEMENTS:

TENSILE STR.: na YIELD PT: na
ELONG.: na RED. OF AREA: na
HARDNESS: na

ALLOY: CDA 122 HEAT: E472 MILL: na

ELEMENTS: Cu-99.9 min: P-.015/.040:
ELEMENTS:

TENSILE STR.: na YIELD PT: na
ELONG.: na RED. OF AREA: na
HARDNESS: na

ALLOY: 4140 HEAT: D895 MILL: LUKENS STEEL

ELEMENTS: C-.38: Mn-.88: P-.012: S-.011: Si-.26: Cr-.95: Mo-.18: V-.013:
ELEMENTS: Cb-.007

TENSILE STR.: na YIELD PT: na
ELONG.: na RED. OF AREA: na
HARDNESS: na

CITY OF SAN DIEGO-WATER PRODUCTION

COMPLETE CHEMICAL ANALYSIS MONTHLY REPORT

MONTH: SEPTEMBER 1986

All values in milligrams/liter, unless otherwise specified

SAMPLE POINT	ALVARADO INFLUENT	ALVARADO EFFLUENT	MIRAMAR INFLUENT	MIRAMAR EFFLUENT	LOWER OTAY INFLUENT	LOWER OTAY EFFLUENT	SD.SD.RES EFFLUENT	SAN DIEGO AQ #1	SAN DIEGO AQ #2/RAW
GENERAL MINERAL									
Calcium	47.2	49.6	46.4	49.6	32.8	35.2	40.8	60.8	45.6
Magnesium	20.2	20.4	19.7	19.7	18.7	18.2	18.7	23.5	20.2
Sodium	55.2	56	58	58.5	59.5	63	65	70.5	62
Potassium	4.59	4.63	4.43	4.46	4.93	4.85	4.67	4.76	4.39
Iron	0.151	0.027	0.932	0.061	0.105	<0.010	0.045	0.03	0.273
Manganese	0.028	<0.006	<0.006	<0.006	0.155	<0.006	<0.006	<0.006	<0.006
Copper	0.01	0.014	0.203	0.015	0.006	0.007	<0.005	<0.005	0.009
Zinc	<0.008	<0.008	<0.008	<0.008	<0.008	<0.008	<0.008	<0.008	<0.008
Sulfate	141	140	145	148	36	41.5	95	194	140
Phosphate-Total	0.242	0.117	0.262	0.218	0.19	0.044	0.117	0.117	0.258
Phosphate-Ortho	0.185	0.036	0.093	0.081	0.19	0.024	0.028	0.056	0.141
Phosphate-Poly	0.057	0.081	0.169	0.137	0	0.02	0.089	0.061	0.117
Silica	14.4	13.4	14.1	10.7	22.4	20.4	14.2	11.7	13.3
pH (pH units)	8.2	8.3	8	8.2	8.25	8.3	8.2	8.2	8.1
P. Alkalinity(to pH 8.3)	0	0	0	0	0	0	0	0	0
T. Alkalinity(to pH 4.5)	105	105	101	101	148	138	120	123	104
T. Hardness(as CaCO3)	202	209	198	206	160	164	180	250	198
Ca. Hardness(as CaCO3)	118	124	116	124	82	88	102	152	114
Chloride	59	63.9	60.6	64	80.8	88.8	75.9	57.7	57.2
Conductivity(at std temp)	673	686	693	706	602	627	650	770	656
Total Solids	441	452	454	456	380	380	415	534	450
Carbonate	0	0	0	0	0	0	0	0	0
Bicarbonate	128.1	128.1	123.2	123.2	180.6	168.4	146.4	150.1	126.9
Non-Carb. Hard.(as CaCO3)	97	104	97	105	12	26	60	127	94
MBAS(Detergent)	0.115	0.066	0.027	0.044	<0.024	<0.024	<0.024	0.044	<0.024
GENERAL PHYSICAL									
Turbidity(NTU)	2.5	0.2	4	0.2	3	0.14	0.16	1.2	4.3
Color(Color Units)	10	1	16	2	25	1	1	1	6
Temperature(Deg. Cent.)	22.2	22.3	22.3	22.2	22.3	22.6	22.9	23.6	23.3
Threshold Odor(Odor Units)	2	<1	1	<1	8	1.4	<1		
pHs	7.82	7.79	7.84	7.81	7.82	7.81	7.80	7.61	7.81
Langlier	0.38	0.51	0.16	0.39	0.43	0.49	0.40	0.59	0.29
Ryzner	7.43	7.29	7.68	7.42	7.38	7.32	7.40	7.02	7.52
INORGANIC									
Arsenic	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005	<0.005
Barium	0.09	0.09	0.11	<0.08	0.1	0.083	<0.08	0.13	0.13
Cadmium	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Chromium	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
Lead	<0.002	<0.002	<0.002	0.0033	<0.002	0.0027	0.005	0.0043	0.0043
Mercury	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002	<0.0002
Selenium	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005	<0.0005
Silver	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004	<0.004
Fluoride	0.07	0.0925	0.105	0.11	0.15	0.19	0.15	0.15	0.12
Nitrate	0.43	2.45	0.77	1.04	1.04	3.02	0.61	0.34	0.54

MANUFACTURERS' TECHNICAL DATA

STAINLESS STEELS

Type	Standard Wrought (Body Centered Cubic)	Austenitic (Face Centered) Cubic)	Non Magnetic More Than 7% Nickel	Description of Corrosion Resistance	Cost AISI B1112 Equals 100
304	"	"	"	General purpose stainless with good mechanical properties and excellent resistance to atmospheric corrosion and a large number of corrosion media.	100
304L	"	"	"	Extra low carbon content avoids harmful carbide precipitation due to welding. Excellent resistance to a wide range of corrosives and atmospheric exposures.	108
316	"	"	"	Best corrosion resistance of the standard stainless steels. Resists pitting and most chemicals. High temperature strength.	151
316L	"	"	"	Extra low carbon variation of 316 to avoid carbide precipitation due to welding. Same excellent corrosion resistance of 316. (13)	159
444	"	Martensitic	Magnetic Little or No Nickel	Immune to chloride stress corrosion cracking. Stabilized against sensitization to intergranular attack. (14)	202

INDEX

1) Stainless Steel Tanks:

Tank design & specifications

Manufacturing specification & estimated times

2) Mild Steel coated Tank

3) Copper Tank

APPENDIX D

BILLS OF MATERIAL

30 U.S. GAL

DIMENSIONS 22 ø outside X 30 high outside
18 ø inside X 26 high inside

MATERIALS

1	Type 304 SS X 16ga 56.5 X 24
2	Type 304 SS X 16ga X 21 X 21 tank ends
5	SS SCH 40 NPT pipe nipples X 3/4" X 4"
1	SS SCH 40 NPT pipe nipples X 1/2" X 4"
1	MS Satin coat galv. 26ga 70 1/8 X 30
2	MA Satin coat galv. 26ga 22 X 22 ends
2	Pipe 3/4 X 14" for coils
1	Strap SS coil support 2X 36 X 16ga
8	Grommets
	Paint & Thinners
1	Isocyanurate foam @ 6.50 Ft3
1	Package & Supports

PRICES FOR JACKETED TANKS with/without HEAT COILS

40 U.S. GAL

Dimensions 22 ø outside X 38 high outside
18 ø inside X 35 high inside

MATERIALS

1	Type 304 SS 32 X 56.5 X 16ga tank skin
2	" " " 21 X 21 X 16 ga tank ends
5	S.S. 3/4 ø NPT nipples X 4" Sc 40 type 304
1	S.S. 1/2 ø NPT nipples X 4" " " " "
1	M.S. Satin coat galv. 38 X 70 1/8 X 20 ga jacket
2	M.S. Satin coat galv. 22 X 22 X 20 ga
1	Pipe 1 (3/4) X 20 Coils S.S.
1	Strap S.S. coil support 2" X 36" X 16ga
8	grommets .....
	paint & thinners (priced @ U.A.P auto paint)
	isocyanurate foam @ 6.50 ft3 mmtl
1	packaging (box & support)

JACKETED TANK PRICING

60 U.S. GAL

Dimensions 22 ø Outside X 54
8 ø inside X 48

Materials

1	Type 304 SS 48 7/8 X 56.5 X 16ga
2	Type 304 SS 21 X 21 X 16ga
5	SS NPT 3/4 ø pipe nipple X 4"
1	SS NPT 1/2 ø pipe nipple X 4"
1	MS satin coat galv. 20ga X 70 1/8 X 54
2	MS satin coat galv. 20ga X 22 X 22
1	Pipe (3/4) X 28' coil SS @ .50/ft
1	Strap SS coil support 2" X
8	Grommets
	Paint & thinners
	Isocyanurate foam contract price 6.50 ft3
1	Package (box & support)

70 U.S. GAL

DIMENSIONS	28 outside X 41	high outside
	24 inside X 38	high inside

MATERIALS

1	Type 304 SS 76 X 25 X 16ga
2	Type 304 SS 30 X 30 X 16ga
3	Type 304 SS 3/4 NPT Nipples X 4"
1	Type 304 SS 1/2 NPT Nipples X 4"
1	Satin coat galv. MS 26ga 89" X 41"
2	Satin coat galv. MS 26ga 30" X 30"
2	Type 304 X 3/4 X 28' pipe coils
1	Strap SS coil support X 2" X 16ga
8	Grommets (+Screws)
	Paint & thinners
	Isocyanurate foam MAT'Ls @ 6.50 ft3
	Package & Supports

80 US GAL

DIMENSIONS	28 outside X 46	high outside
	24 inside X 42	high inside

MATERIALS:

1	Type 304 SS 1.20/lb 76 X 30 3/4
2	Type 304 SS 30 X 30 X 16ga tank ends
5	Type 304 SS 3/4 NPT X 4" Nipples
1	Type 304 SS 1/2 NPT X 4" Nipples
1	Satin coat galv. MS 88 X 46
2	Satin coat galv. MS tank ends 7.5# 30 X 30
2	Type 304 SS X 3/4 X 40' Pipe coils
1	Strap SS coil support X 2" X 16ga
8	Grommets (+Screws)
	Paint & thinners
	Isocyanurate foam 6.4 ft3 @ 6.50
	Package & supports

100 US GAL

DIMENSIONS	28 outside ø X 55	high outside
	24 inside ø X 51	high inside

MATERIALS

1	Type 304 SS 16ga 76 X 39
2	Type 304 SS 16ga 26 X 26 ends
5	Type 304 SS 3/4 X 4" NPT nipples
1	Type 304 SS 1/2 X 4" NPT nipples
1	Satin coat galv. MS X 26ga X 88 X 55
2	Satin coat galv. MS X 26ga X 30 X 30
2	Type 304 SS X 3/4 X 56 pipe coils
1	Strap 304 SS x 2" X 16ga pipe support
8	Grommets
	Paint & thinners
	Isocyanurate foam MAT'Ls
	Package & supports

JACKETED TANK PRICING

120 US GAL

DIMENSIONS 28 ø outside X 64 high outside
24 ø inside X 60 high inside

MATERIALS

1	Type 304 SS 76 X 48
2	Type 304 SS 30 X 30
5	Type 304 SS 3/4 X 4 pipe nipple NPT
1	Type 304 SS 1/2 X 4 pipe nipple NPT
1	Satin coat MS galv. 26ga 88 X 64
2	Satin coat MS galv. 30 X 30
2	Type 304 X 3/4 X 60' pipe coils
1	Strap SS coil support 2" X 16ga
8	Frommets & Misc. Screws
	Paint & thinners
1	Isocyanurate foam
1	Package & supports

MANUFACTURING SPECIFICATIONS & ESTIMATED TIMES

A) To make SS inner tank

Welding times : Estimated

1) To cut skin & cut holes in skin approx. 5 min. per tank.

2) Roll tank skins average 1 1/2 min. each roll for 3 min./skin
set up rolls average 20 minutes.

3) Tack tank skins & handle for preparation to auto weld
average each 2 minutes.

4) To weld tanks on machine long seam
handle & weld 5 minutes rate approx. 24"/min

5) Tack ends on tanks - average using jig 7 min/end (ie 14 min/tank)

6) To weld heads ø hds & handle 6 1/4 indicates 48"

7) To roll and make coil approx. 35 min./coil.

8) Couplings & Nipples average 5 minutes each are typical of all tanks to place, tack and weld.

9) Pressure test tank only - average using tank immersion 10 min.
30 gal size,
40 gal add 2 min 80 gal add 5 min
120 gal add 10 min.

10) Pressure test coils to 150 PSI - average 6 min. ea

11) To passivate, handle, wash, etc. add 35min/tank average.

12) To manufacture heads 12 min. per tank 18"
18 min. per tank 24"

B) SKINS - JACKET

Prepainted Galvanized
Delivered pre cut to size

1) Layout/drill fittings - Use Jig — 12 min. per tank

2) Roll seam connection — set up — 15 min. per tank

3) Roll skin to diameter — set up / roll — 3 min. per tank

4) Spin heads — 6 min. per tank

5) Preparation of Tank
   To block bottom, sides, insert grommetts, tape potential leak areas
   * place foaming lid — 15 min.

*Suggest a silicone caulk bead around potential lead areas such as bottom cap joint, nipple holes just prior to inserting grommets could reduce clean up time to '0' adds approx. 5 minutes.

FOAMING

C) Foam - Poured Foam

Affix lid for foaming	2	
pour into tank	2 min.	
remove foaming lid	2 min.	] 22-25 each
place permanent lid	1 min.	
clean up/level	15 min.	*

Packaging - Fold box

Place foam block at bottom	
lower tank into box	
place top block	] 5 min. each
close, tape	
pallatizing	

JACKETED TANKS

prepaint material VS SHOP PAINT

A major consideration is not using the prepainted MT'L is the fact that it is very easy to scratch or damage and thus costly to handle and hard to touch up .

Prepainted MT'L 24 ga MS price @ $.682/lb or $.79/ft2
M.S. cold rolled 20 ga 32.50/cut

THEN:

Paint supplier Glidden

Primer (recommended) #5210 (39% solids content) 21.89(26.06tip)gal(4P)
1 1/2mil coverage ~ 750□ = 3.4¢ /Ft2

Primer (alternate) #5209 (23% solids content) 13.30 (15.77tip) gal(4£)
1mil coverag ~ 450□ = 3.3¢ /ft2

Top coat - Glidden polyeupethane Industrial enamel
6000 series (can have any color mixed) $ 18.00/4l
(21.18tip) coverage ~ 900□ = 2¢ /ft2

Recommends primer for best adhesion of top coat. Clean surface with lauquer thinners prior to painting to eliminate shop film etc. Maintain temp at 50º F + for best results.

Thinners for primer - mineral spirits or naptha # 5568 solvent.

PRE-PAINT MTL VS SHOP PAINT

Based on a min. Qty. of 20 AM 40 tanks
Shop labor @ $35/hr

SET-UPS (includes clean sprayer)	2
CLEAN DKINS (wipe down)	2
COVER NIPPLES ETC use plastic caps	1
APPLY PRIMER (alkyd)	5
APPLY ACRYLIC TOP COAT	5
	15 min. @ 58¢/min. = 8.70 labor

MATERIALS AM40 HAS 32 □ area

Lacquer thinners	~ 25¢/tank=	.25
Paint thinners @	~ 10¢/tank=	.10
Primer(cheaper)	3.3¢/ft2=	1.05
Top coat	@ 3.0¢/ft2=	1.00 allows for over spray & waste
		2.40/ tank MtL's primed or
		1.35 NOT PRIMED

Cost per Ft2 Primed = 11.10 ÷ 32 35¢ = 11.20 per AM40
Cost per Fts Not Primed = 10.20 ÷ 32 32¢ = 10.25 per AM40

As above using a fast dry alkyd enamel @ 27.54/gal.
Coverage is 480□/gal. = 6¢/Ft2
Add 10¢ /tank thinner & add 77¢ 3.43 primed
2.37 not primed

Price with labor - primed / Ft2 = 38¢ = 12.16 per AM 40
No prime / Ft2 = 35¢ = 11.20 per AM 40

polyeurethane high abrasion resistance
PRE PAINT VS SHOP PAINT

20 ga pre paint - not available
22 ga pre paint - not available

For ease of handling VS price, recommend 20 ga Mild Steel
Not primed at 81¢/Ft2

- less care in handling
- less susceptable to damage in shipping
- less care required when foaming (shape)

INSULATION OF AM TANKS

ESTIMATED IN HOUSE PRICE - MOLDED HALVES

MOLD - To fabricate molds to pour foam and clamp shut.

LINER FOR MOLD so FOAM WILL NOT STICK - per 1/2
price from N/W shipping

Labor	To prepare mold (set liner in)	1
	To set up foam machine	1
	To pour	2
	To clamp mold shut	1
	To seperate mold & shell	5
		10 = 5.80 X 2 = 11.60/tank

Chemical per tank (AM40) @ $1600/380ft2=4 21/ft3 plus labor

say $16 to allow for waste and cleanup 27.60 ea

Small Labor/MAT'L saving may be even less if the cost of the molds is considered, however.
Advantage is that should servicing be req'd, they are much easier to disassemble.
Less clean up is required for shop painting.
No strapping req'd to hold insulation in place for skin application.
Still have R 14 insulation factor, not susceptable to moisture.

APPENDIX E

COPPER 40 GAL (US) TANKS
alloy 110 or 122 Copper

1) Copper manufacturing specificatins & pricing

Material

48 X 48 X 9ga @ 5.304# X $ 1.85/lb X 115= 180.55
20 X 20 X 7ga @ 6.691# X $ 1.85/lb X 2= 79.08

Labour

To roll sheet (2 required)	2
To circle cut ends	1
To stamp ends/trim	1 1/5
To weld skin	4
To weld heads (no tacks required)	6
To draw fittings	10
To handle (extra weight)	10
To pressure test	10
To prepare for shipping	2
	46 1/5 @ 35/hr= $27.50

366.21

2) 22ga Copper Fiberglass reinforced

MATERIAL

48 X 48 X 22ga @ 1.250#/ft X 1.85/lb X 1.15 = 42.55
20 X 20 X 7ga @ 6.91 / X 1.85 X 1.15 = 79.08
E Glass cloth - 62□ = 7yds @ 4.60 = 32.20
Epoxy resin 3£ @ 14.67 = 44.00

LABOUR

To roll	2
Circle cut	1
Stamp ends/trim	1 1/5
Weld skin	3
Weld Heads	4
Weld reinforce PL for fittings (solder)	10
Make reinforce Pls	2
Draw fittings	10
Handle (care against dents)	5
Wrap in F/G	45
Set for cure/moveing/handle	3
Test-probably not required say 1 in 10	2
Shipping	1
	90 @ 35/hr = $52.50

250.33

BRONZE (Alloy 464)

MATERIAL

48 X 48 X 14ga X 2.843#/Ft2 X $ lb
20 X 20 X 12ga X 3.584#/Ft2 X $ lb

LABOUR

To Roll	2
Circle cut ends	1
Stamp ends/trim	1/5
Weld skin	4
Weld heads (no tack required)	6
Draw fittings	10
Handle (extra weight)	5
Pressure test	10
Prep for shipping	2
Fittings hds to tank	5
	45 1/5 @ 35/hr say 27.50
	166.63

BRONZE VS STAINLESS STEEL 40 GAL (US) TANKS

Using Bronze Alloy 464 ty=25000 PSI

Assume labor equal to SS tank for rolling and welding. Use tool to make fittings in skin. These fittings may require soldering on end caps to test loosing time savings gained not welding fittings.

Using existing times, reduce for fittings allow 50 min. ea

To determine MtL gauge

$$t = \frac{dp}{2s} = \frac{15.625 \times 200}{2 \times 25000} \qquad \frac{3125}{50000} = .0625 \quad \text{sides}$$

$$t = \frac{dp}{2s} = \frac{15.625 \times 200}{2 \times 25000} \times 1.34 \qquad \frac{3125}{50000} \times 1.34 = .08375 \quad \text{ends}$$

Then walls weight = (48" X 48") ÷ 144 X 2.843 #/ft2 = 45.5 lb (14ga)

2 ends weight = 2(18 X 18 ÷ 144 X 3.584 #/ft2) = 16.2 lb (12ga)

labor is 29.50 ea

To use Bronze, wrapped with E Glass f/g Ty 250 000 PSI

$$t = dp = \frac{15.625 \times 200}{2 \times 30\,000} \qquad \frac{3125}{60\,000} = .02625 = 3 \text{ wraps @ } 54^{\text{g}}$$

1 wrap would allow resin to "POP" out between weaves. Suggest 3 or 4 wraps as minimum - assume 3 wraps for testing then:

then use bronze 24ga (.0206) @ .8915#/ft2 X 20.5 sq ft = 18.3 lb
use 20.5 X 3wraps = 61.5 sq ft = 7 yds Cloth @ 4.60 = $ 32.20
use 3£ Resin (layin 20 £ lots) = 44.00

F/G= 76.20

Labor to Fab tank less weld time, less fitting time, etc.
40min. ea 23.5 L = 49.75
Labor to Wrap in F/G 45 min. = 26.25 say 50
Bronze tank is 126.20 + Mtl Bronze =
As above for copper Costs = as above 126.20 + Cu =

APPENDIX F

TANK PERFORMANCE RESULTS

30 U.S. gallon tank
40 U.S. gallon tank
40 U.S. gallon tank, double heat exchanger
60 U.S. gallon tank
60 U.S. gallon tank, double heat exchanger
80 U.S. gallon tank
100 U.S. gallon tank
120 U.S. gallon tank

The following tests were conducted:

1. Recovery Test: How long does it take to raise a given amount of water (based on tank size) by a stated temperature rise. This is expressed in time/temperature rise.

2. Delivery Test: Once the tank has been risen to a stated temperature, how much water can be drawn out in 10 min and 1 hour. And how much can be drawn out in 1 hour on a continuous basis (this is based on raising water from ambient levels by 90 F). These tests were conducted for 7, 12, and 21 litres per minute discharge.

3. Heat Loss Test: This measures how much heat is lost from the tank. The tank is raised by 90 F and left to stand with heat loss being recorded.

A & R METALS

30 U.S. gallon (114) L tank

RECOVERY:
Time to average tank temperature of -

50 C	0.73 hours
60 C	1.40 hours

NOTE:
Boiler average supply temperature 80 C (176 F)
flow 11 L/min. (2.9 U.S. gpm)

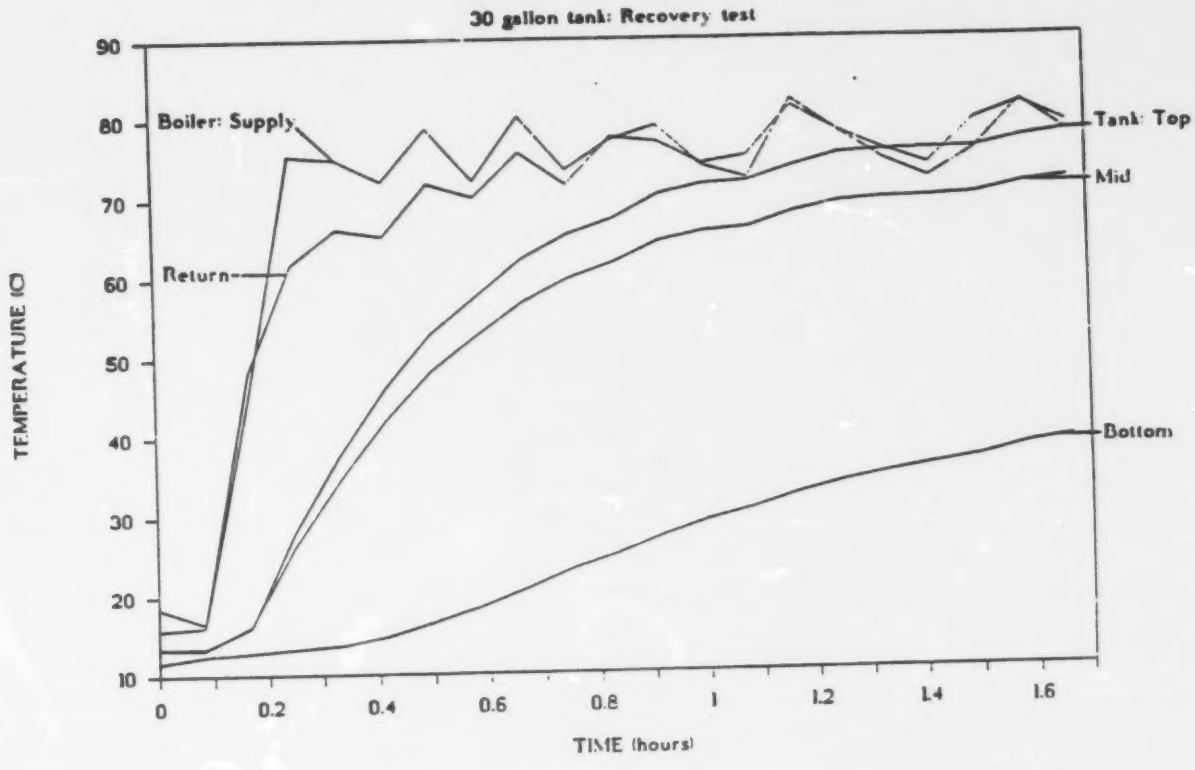
DISCHARGE:

	7 L/minute			12 L/minute			21 L/minute		
	1.8 U.S. gpm			3.2 U.S. gpm			5.5 U.S. gpm		
TEMPERATURE C	QUANTITY L	QUANTITY US gal	ENERGY MJ	QUANTITY L	QUANTITY US gal	ENERGY MJ	QUANTITY L	QUANTITY US gal	ENERGY MJ
>70	83	22	23	70	18	20	68	18	18
>60	87	23	24	74	20	20	68	18	18
>50	92	24	25	78	21	21	68	18	18
>40	125	33	33	81	21	21	68	18	18
>30	unlimited >35 C			104	27	23	83	22	19
				unlimited >28 C			unlimited >19 C		

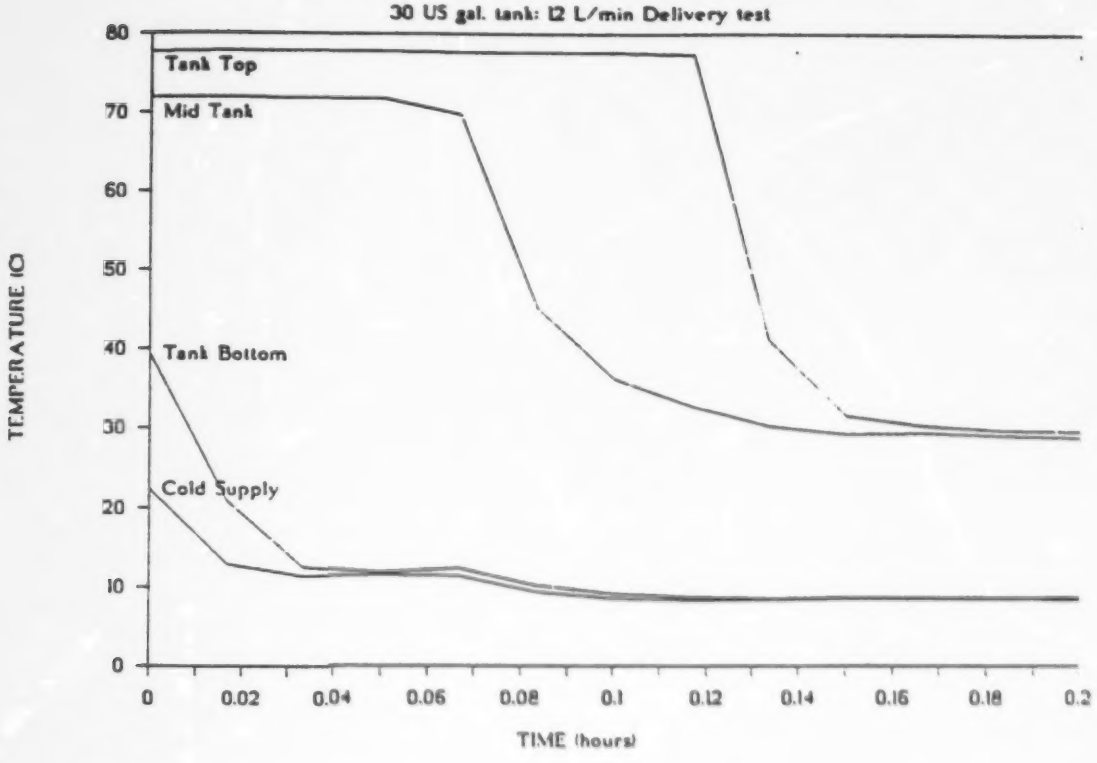
NOTE:
Boiler average supply temperature 80 C (176 F)
flow 11 L/min. (2.9 U.S. gpm)

STANDING HEAT LOSS:
200 W (50 C temp. difference)
1.3 C/hour
2.6 %/hour (50 C temp. difference)

A & R METALS TEST FACILITY



A & R METALS TEST FACILITY



A & R METALS

40 U.S. gallon (151) L tank

RECOVERY:

Time to average tank temperature of -

50 C	0.54 hours
60 C	0.83 hours

NOTE:

Boiler average supply temperature 80 C (176 F)
flow 11 L/min. (2.9 U.S. gpm)

DISCHARGE:

	7 L/minute			12 L/minute			21 L/minute		
	1.8 U.S. gpm			3.2 U.S. gpm			5.5 U.S. gpm		
TEMPERATURE C	QUANTITY L	US gal	ENERGY MJ	QUANTITY L	US gal	ENERGY MJ	QUANTITY L	US gal	ENERGY MJ
>70	115	30	32	100	26	26	97	26	26
>60	121	32	34	111	29	29	102	27	27
>50	135	36	37	122	32	31	108	29	28
>40	190	50	45	134	35	33	117	31	29
>30	unlimited > 37 C			157	41	35	139	37	31
				unlimited >24 C			unlimited >21 C		

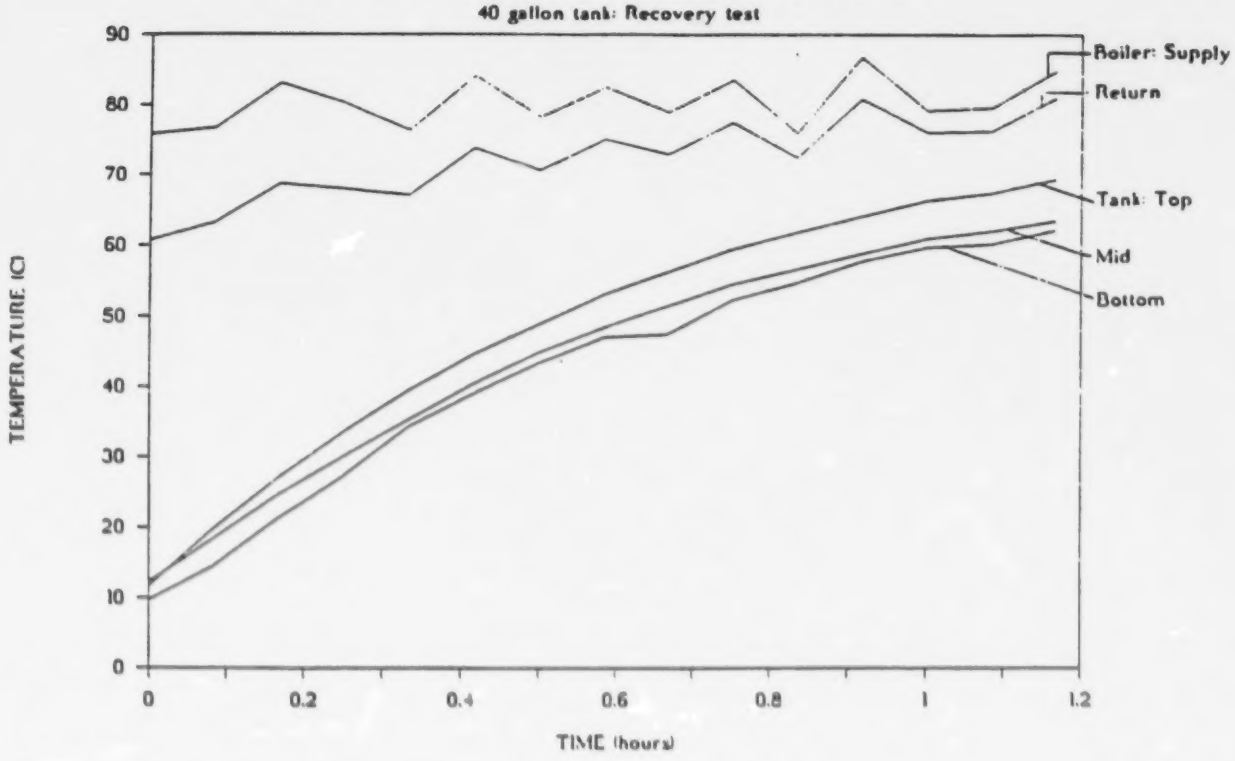
NOTE:

Boiler average supply temperature 80 C (176 F)
flow 11 L/min. (2.9 U.S. gpm)

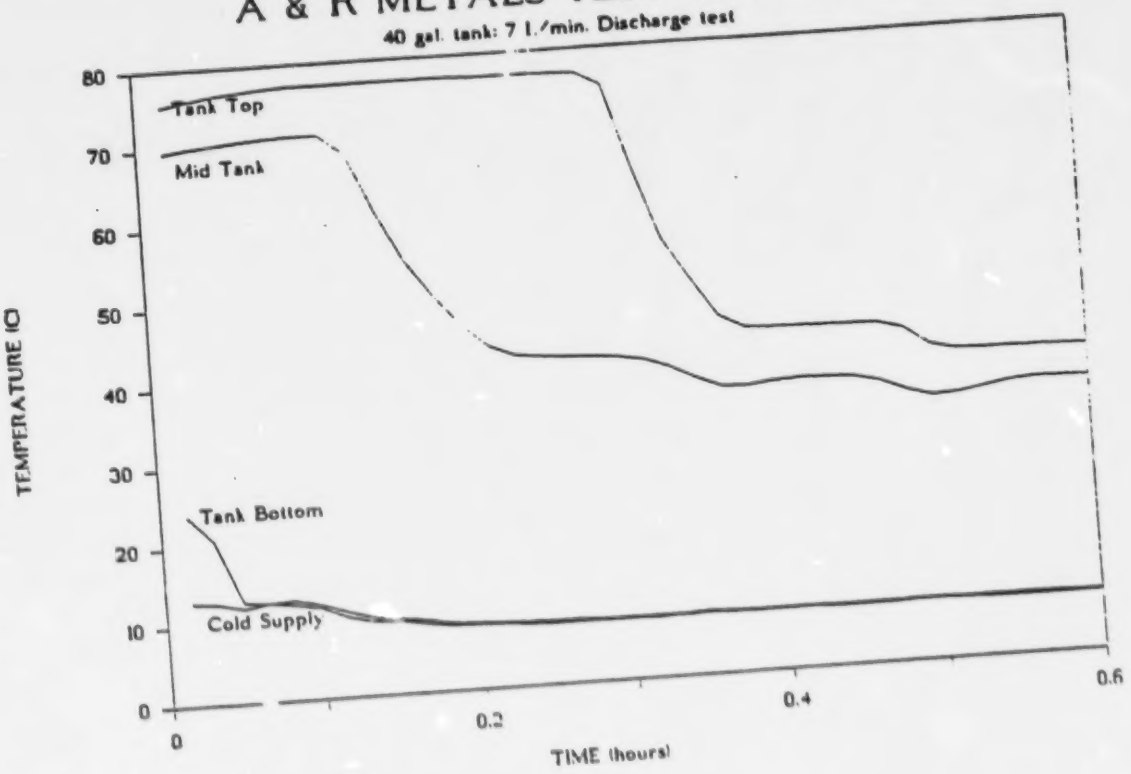
STANDING HEAT LOSS:

240 W (50 C temp. difference)
1.2 C/hour
2.4 %/hour (50 C temp. difference)

A & R METALS TEST FACILITY



A & R METALS TEST FACILITY



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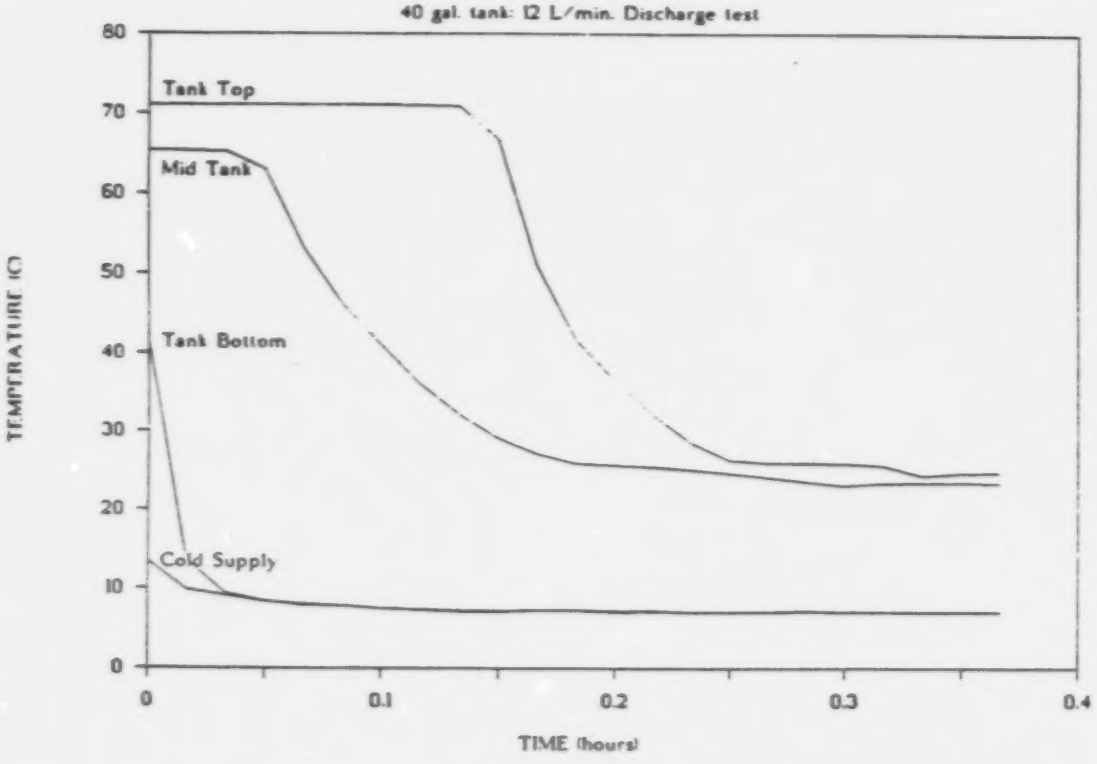

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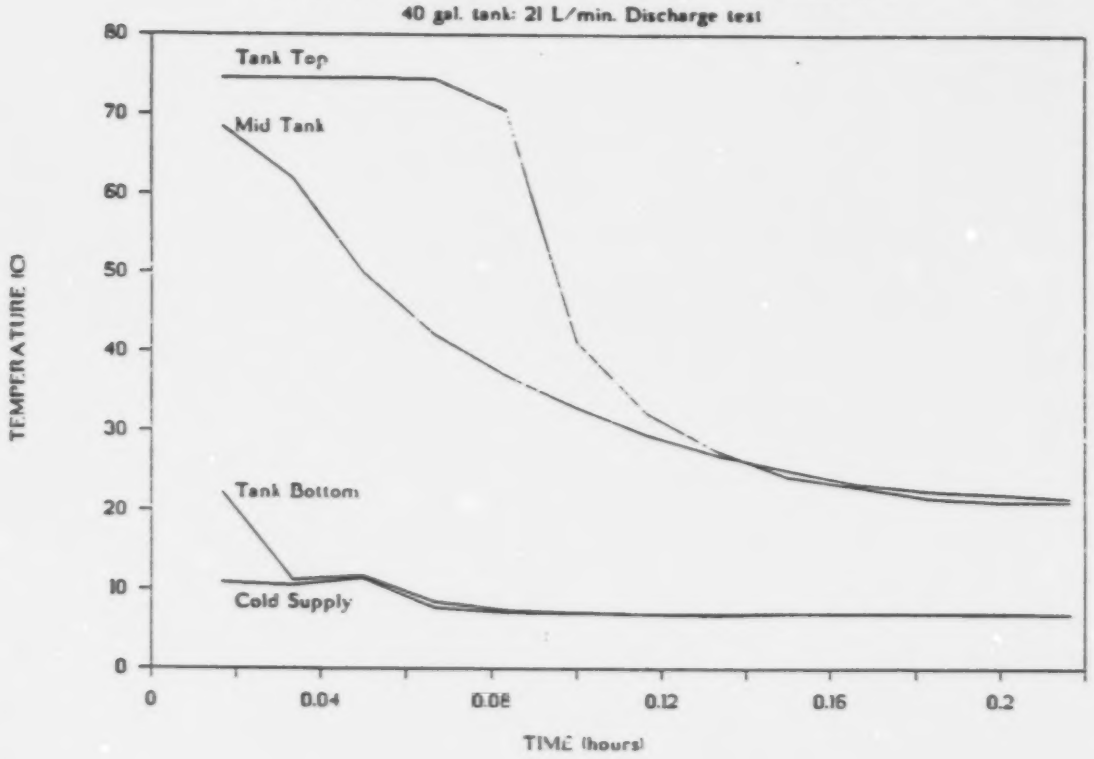

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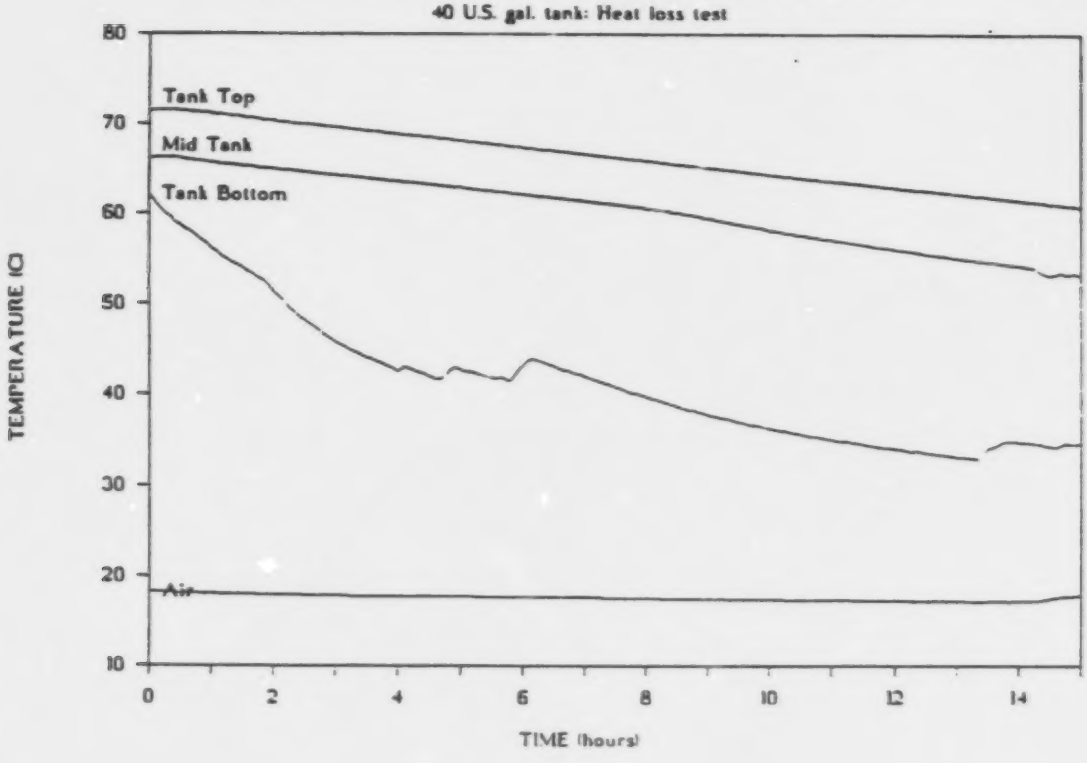


A & R METALS

40 U.S. gallon (151) L dbl heat exchanger tank

RECOVERY:

Time to average tank temperature of -

50 C	0.46 hours
60 C	0.75 hours
70 C	2.62 hours

NOTE:

Boiler average supply temperature 80 C (176 F)
flow 11 L/min. (2.9 U.S. gpm)

DISCHARGE:

	7 L/minute			12 L/minute			21 L/minute		
	1.8 U.S. gpm			3.1 U.S. gpm			5.5 U.S. gpm		
TEMPERATURE C	QUANTITY L	QUANTITY US gal	ENERGY MJ	QUANTITY L	QUANTITY US gal	ENERGY MJ	QUANTITY L	QUANTITY US gal	ENERGY MJ
>70	144	38	39	124	33	34	114	30	31
>60	163	43	43	136	36	36	120	32	32
>50	288	76	63	147	39	38	127	34	33
>40	unlimited >45 C			192	51	45	175	46	41
>30				unlimited >35 C			240	63	54
							unlimited >28 C		

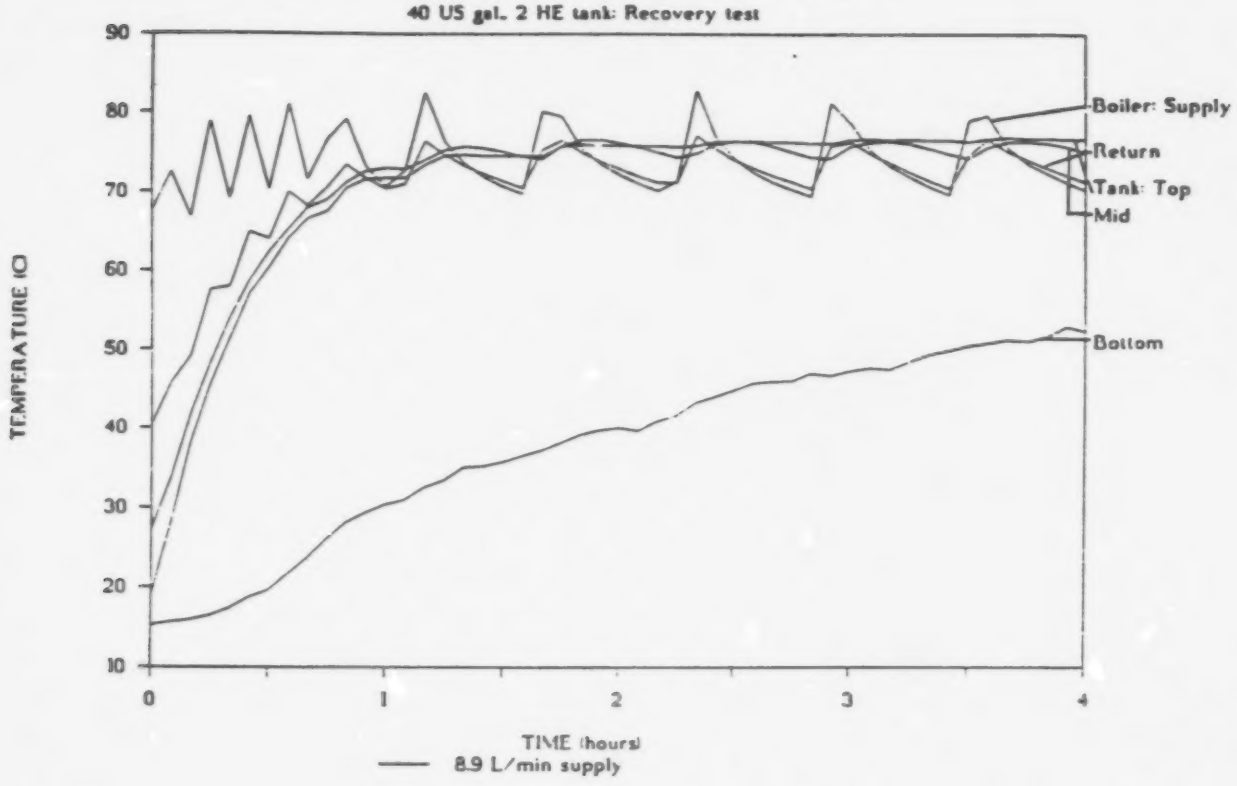
NOTE:

Boiler average supply temperature 80 C (176 F)
flow 11 L/min. (2.9 U.S. gpm)

STANDING HEAT LOSS:

240 W (50 C temp. difference)
1.2 C/hour
2.4 %/hour (50 C temp. difference)

A & R METALS TEST FACILITY



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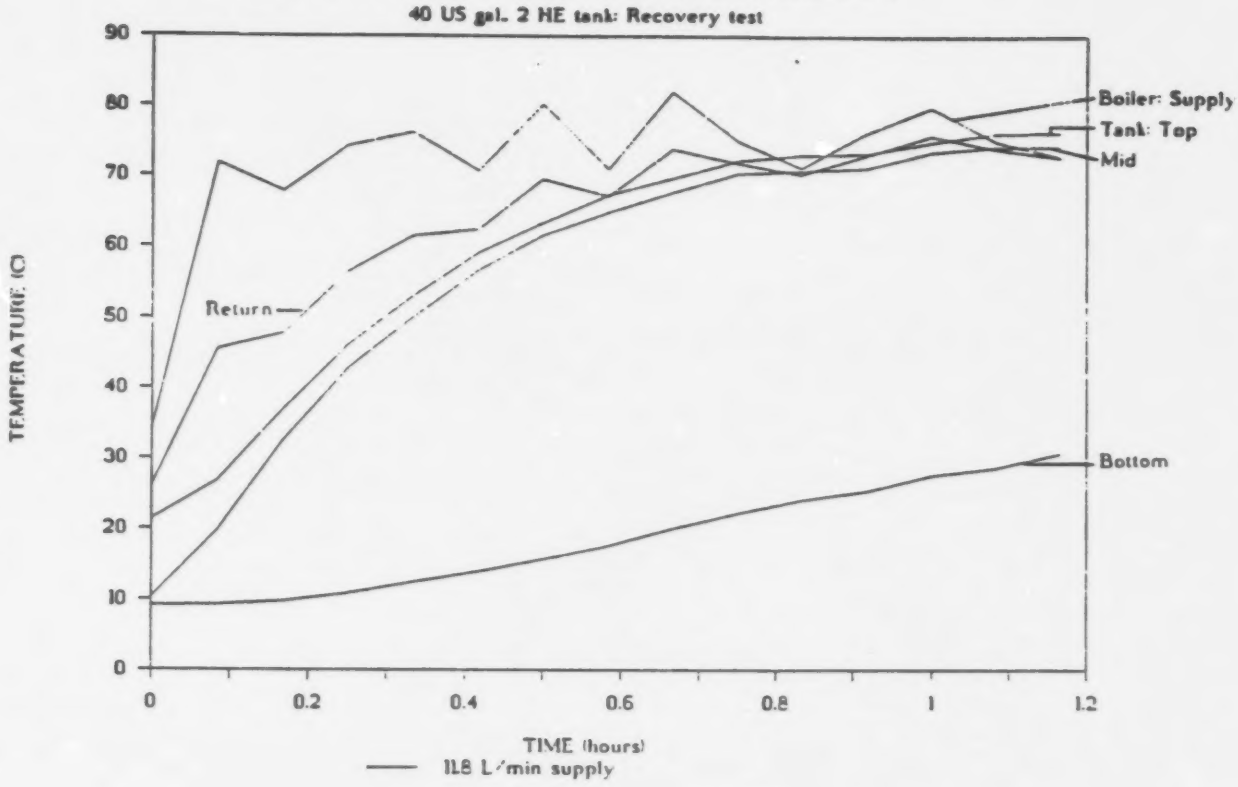

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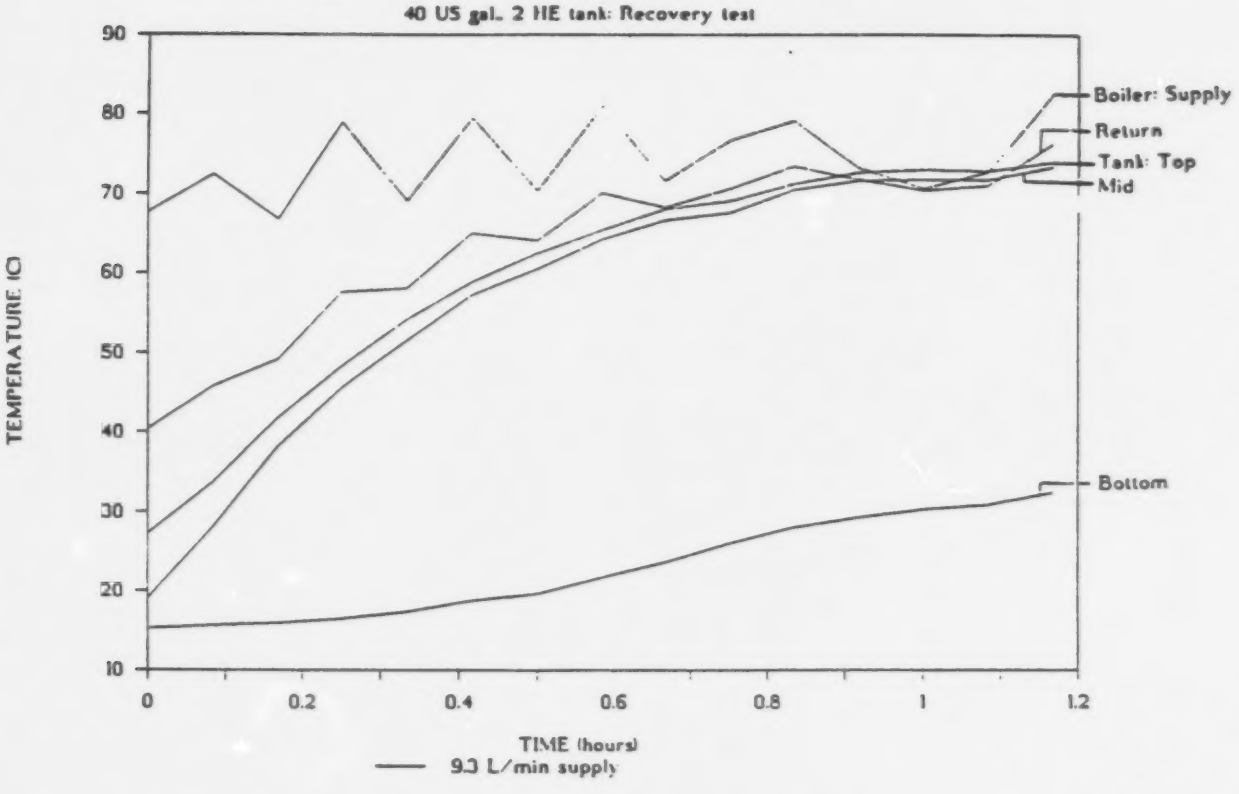

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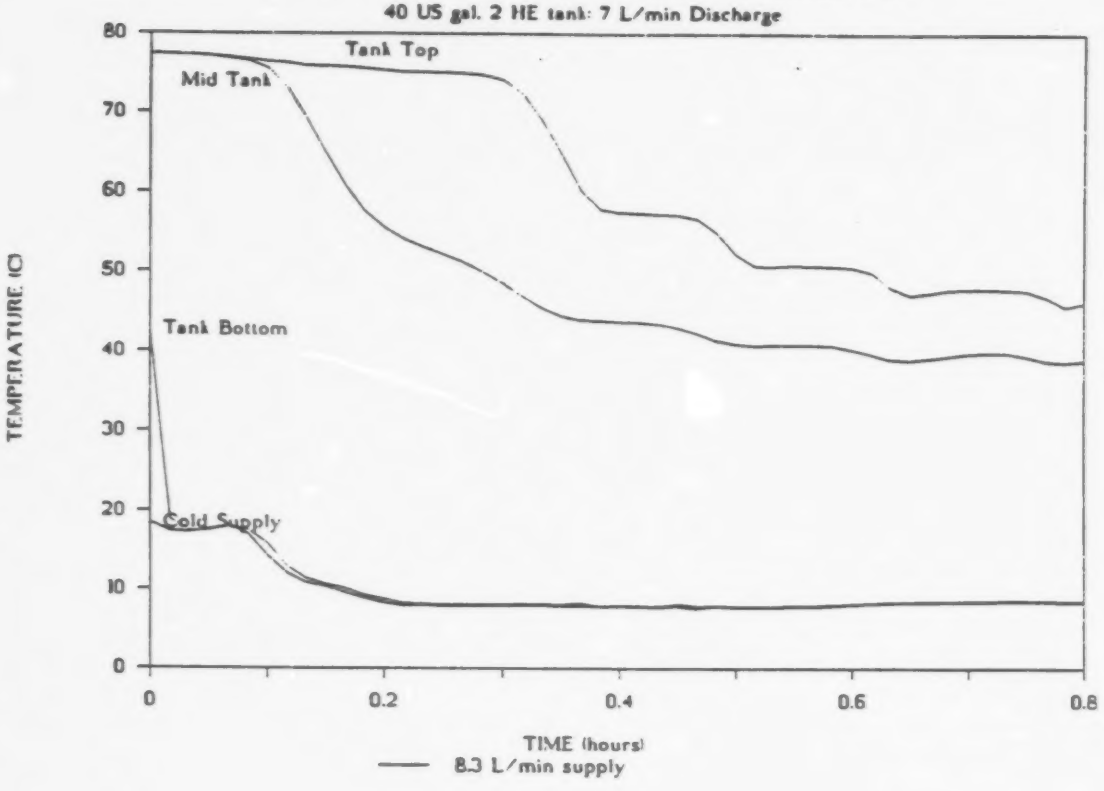

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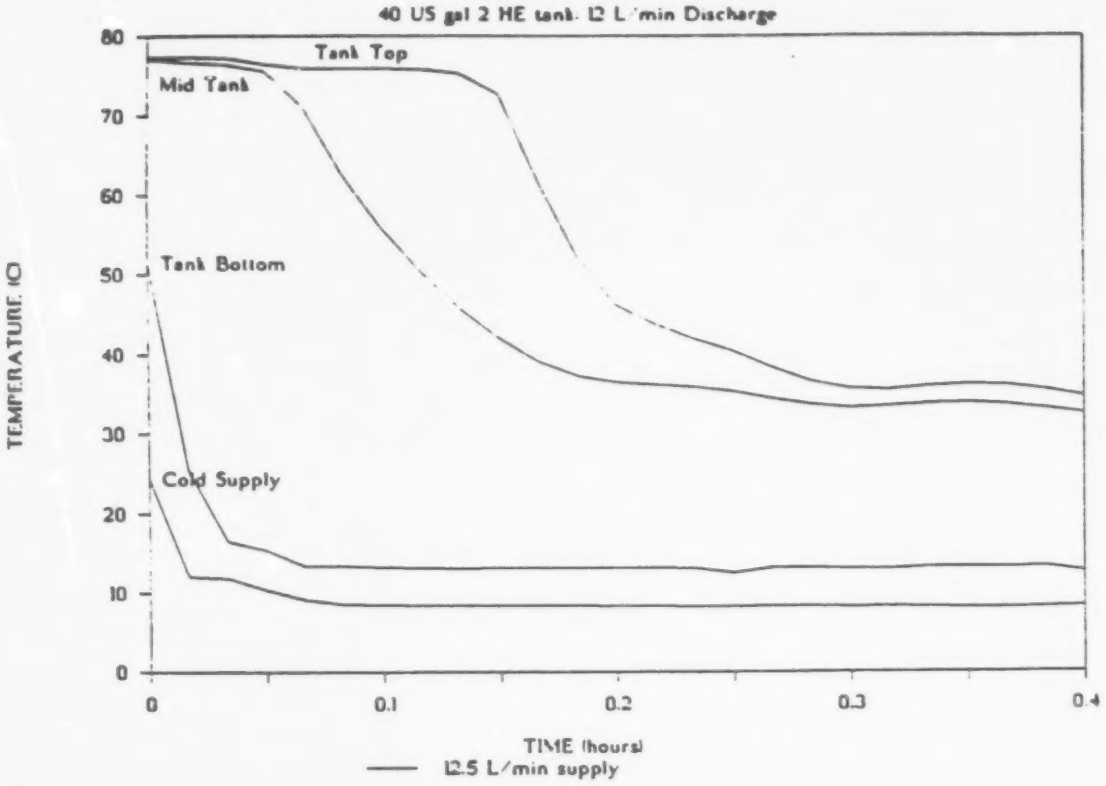


A & R METALS

60 U.S. gallon (227) L tank

RECOVERY:
Time to average tank temperature of -

50 C	0.75 hours
60 C	1.15 hours

NOTE:
Boiler average supply temperature 80 C (176 F)
flow 11 L/min. (2.9 U.S. gpm)

DISCHARGE:

	7 L/minute 1.8 U.S. gpm			12 L/minute 3.1 U.S. gpm			21 L/minute 5.5 U.S. gpm		
TEMPERATURE C	QUANTITY L	US gal	ENERGY MJ	QUANTITY L	US gal	ENERGY MJ	QUANTITY L	US gal	ENERGY MJ
>70	157	41	42	138	36	37	129	34	35
>60	164	43	44	149	39	40	133	35	36
>50	179	47	47	160	42	42	138	36	36
>40	245	65	61	184	49	46	157	41	39
>30	unlimited >39 C			214	57	50	188	50	44
				unlimited >27 C			unlimited >22 C		

NOTE:
Boiler average supply temperature 80 C (176 F)
flow 11 L/min. (2.9 U.S. gpm)

STANDING HEAT LOSS:
315 W (50 C temp. difference)
1.0 C/hour
2.0 %/hour (50 C temp. difference)

A & R METALS

60 U.S. gallon (227) L dbl heat exchanger tank

RECOVERY:

Time to average tank temperature of -

50 C	0.71 hours
60 C	1.05 hours
70 C	2.40 hours

NOTE:
Boiler average supply temperature 80 C (176 F)
flow 11 L/min. (2.9 U.S. gpm)

DISCHARGE:

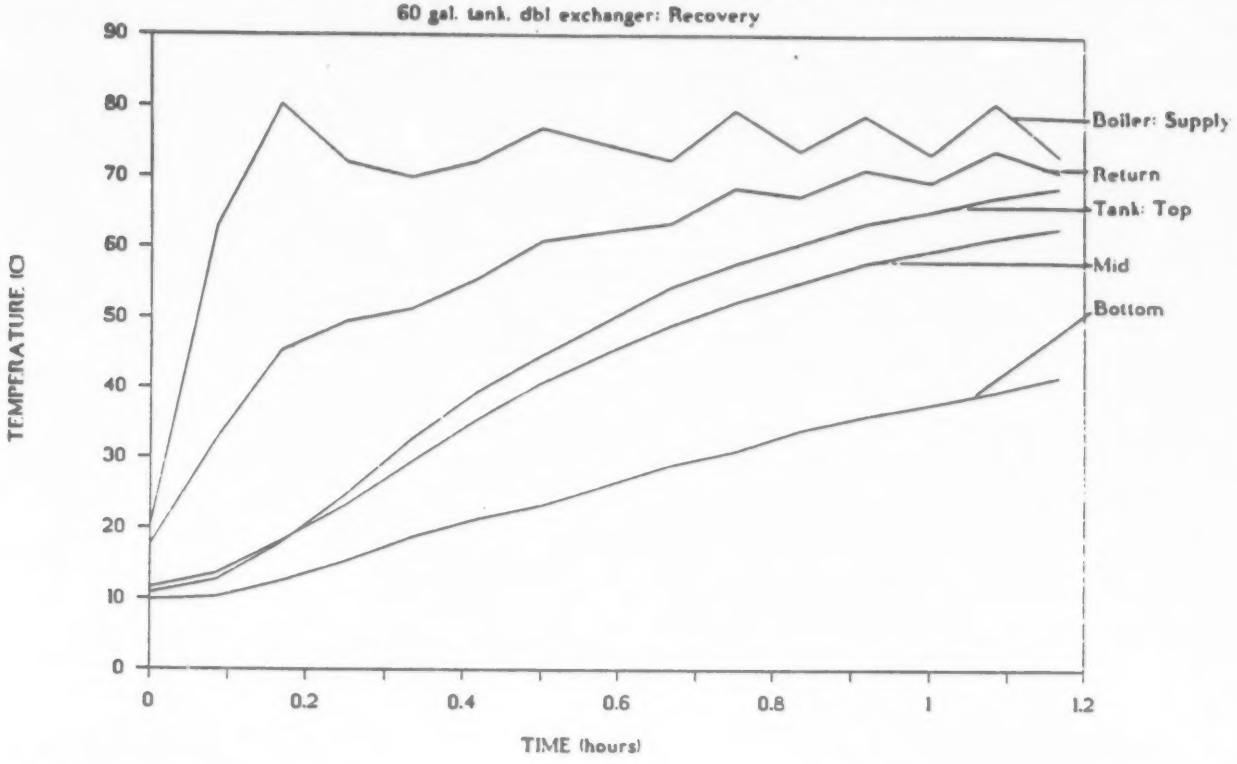
	7 L/minute			12 L/minute			22 L/minute		
	1.8 U.S. gpm			3.1 U.S. gpm			5.8 U.S. gpm		
TEMPERATURE C	QUANTITY L	US gal	ENERGY MJ	QUANTITY L	US gal	ENERGY MJ	QUANTITY L	US gal	ENERGY MJ
>70	175	46	50	171	45	49	168	44	48
>60	190	50	53	184	49	52	175	46	49
>50	305	81	83	197	52	54	184	49	50
>40	unlimited >47 C			250	66	65	192	51	50
>30				unlimited >38 C			unlimited >30 C		

NOTE:
Boiler average supply temperature 80 C (176 F)
flow 11 L/min. (2.9 U.S. gpm)

STANDING HEAT LOSS:

315 W (50 C temp. difference)
1.0 C/hour
2.0 %/hour (50 C temp. difference)

A & R METALS TEST FACILITY



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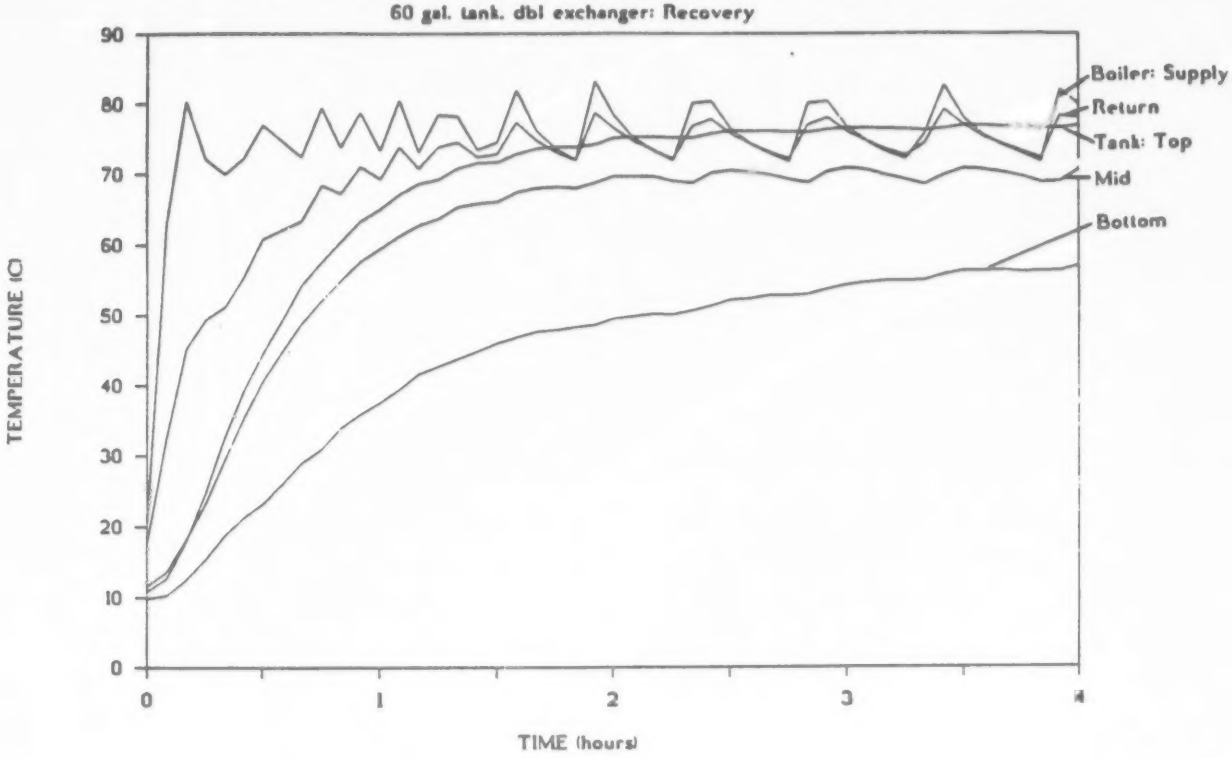

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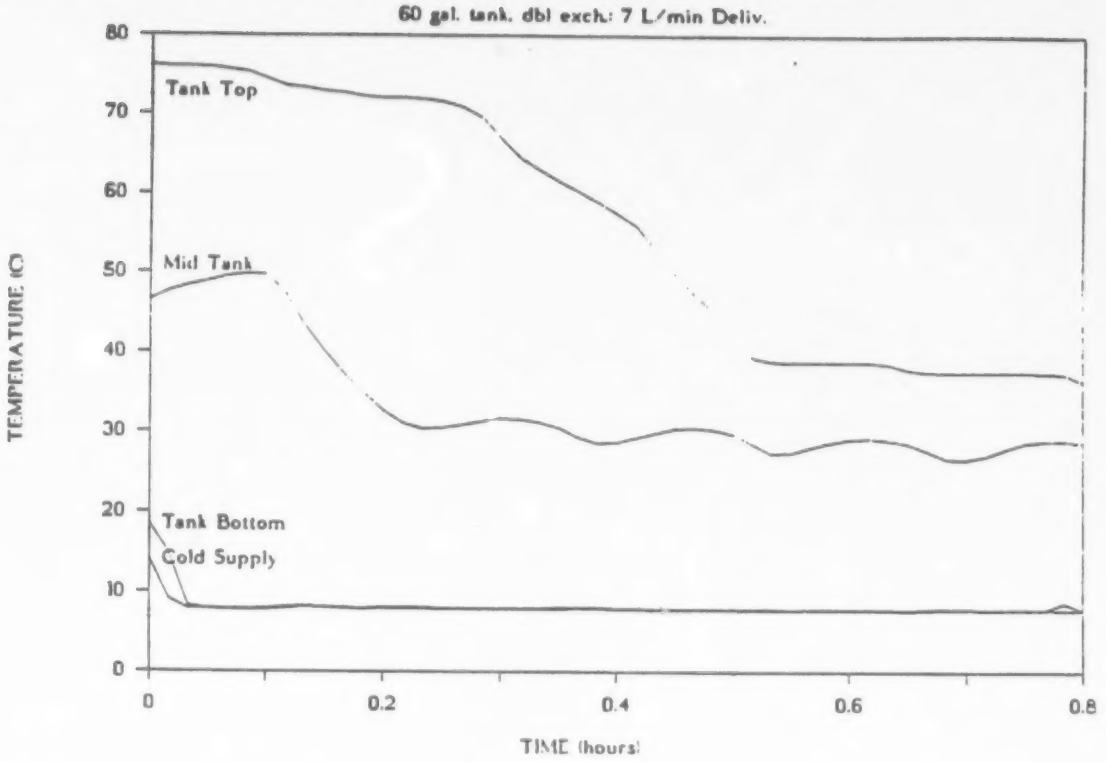

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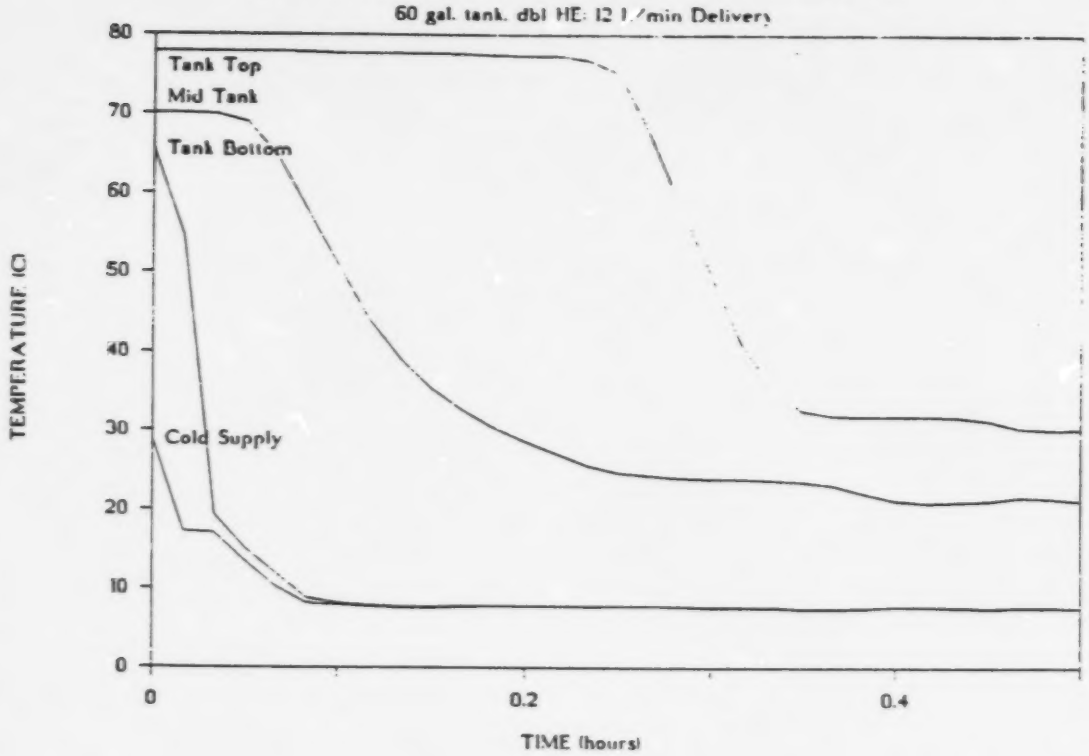


A & R METALS

80 U.S. gallon (303) L tank

RECOVERY:

Time to average tank temperature of -

50 C	0.92 hours
60 C	1.42 hours

NOTE:

Boiler average supply temperature 80 C (176 F)
flow 11 L/min. (2.9 U.S. gpm)

DISCHARGE:

	7 L/minute			12 L/minute			21 L/minute		
	1.8 U.S. gpm			3.2 U.S. gpm			5.5 U.S. gpm		
TEMPERATURE C	QUANTITY L	US gal	ENERGY MJ	QUANTITY L	US gal	ENERGY MJ	QUANTITY L	US gal	ENERGY MJ
>70	205	54	57	176	46	49	149	39	41
>60	214	57	59	187	49	51	155	41	43
>50	232	61	62	199	53	54	162	43	44
>40	unlimited >44 C			235	62	59	195	52	49
>30				272	72	64	232	61	54
				unlimited >29 C			unlimited >23 C		

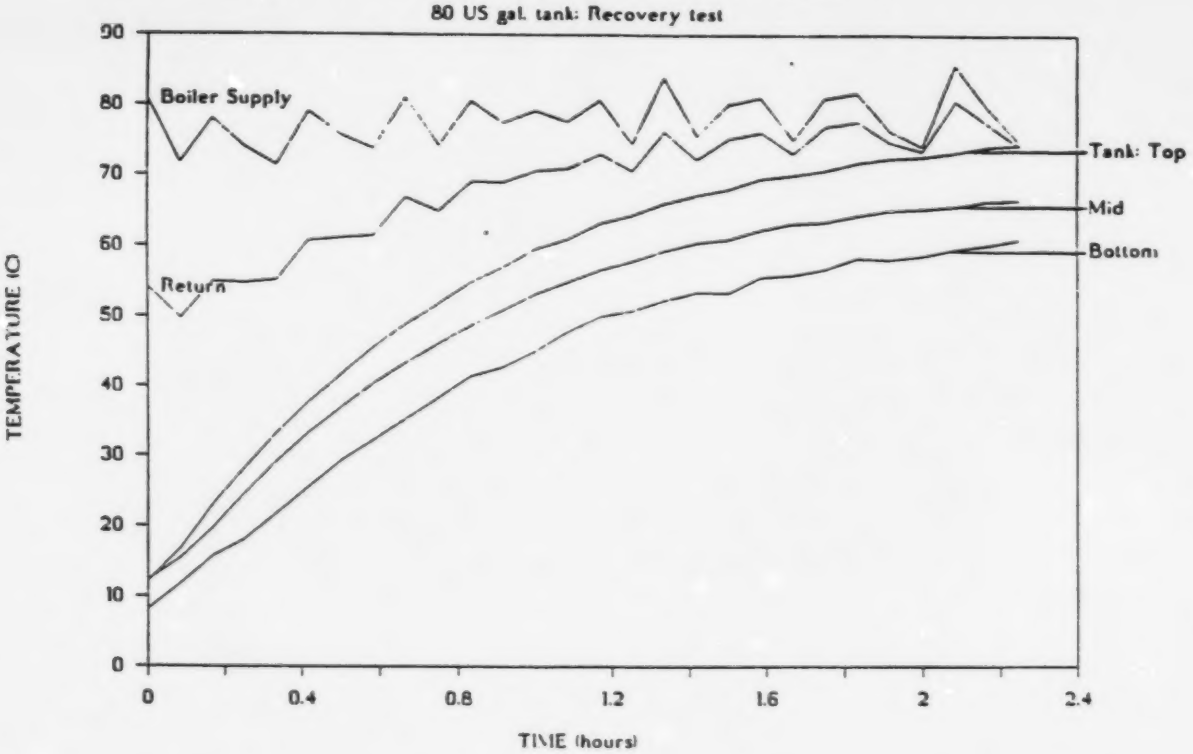
NOTE:

Boiler average supply temperature 80 C (176 F)
flow 11 L/min. (2.9 U.S. gpm)

STANDING HEAT LOSS:

320.0 W (50 C temp. difference)
0.8 C/hour
1.6 %/hour (50 C temp. difference)

A & R METALS TEST FACILITY



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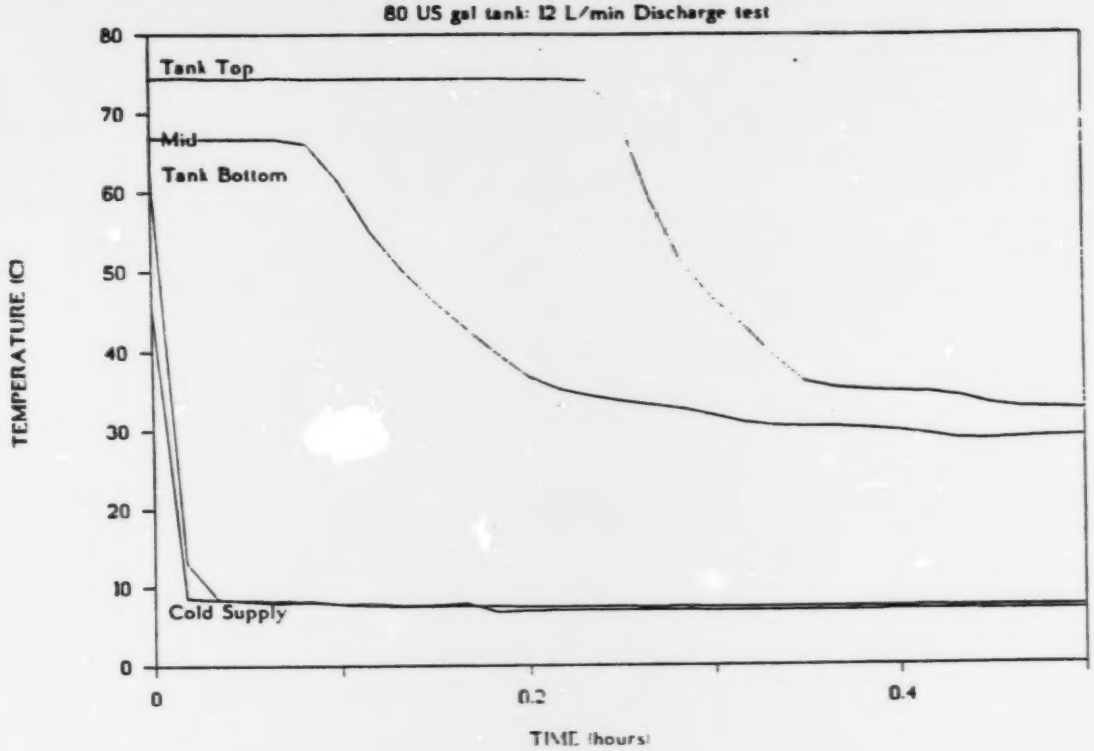
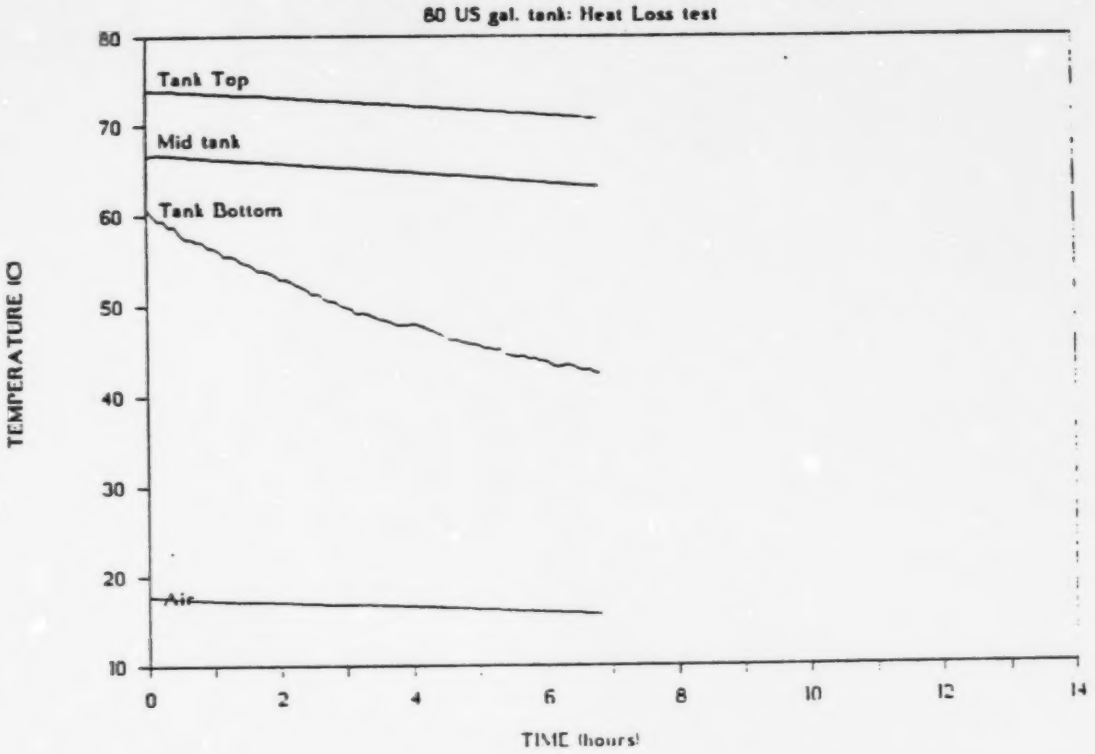


A & R METALS TEST FACILITY



A & R METALS

100 U.S. gallon (379) L tank

RECOVERY:

Time to average tank temperature of -

50 C	0.83 hours
60 C	1.33 hours
70 C	2.20 hours

NOTE:

Boiler average supply temperature 80 C (176 F)
flow 11 L/min. (2.9 U.S. gpm)

DISCHARGE:

	7 L/minute 1.8 U.S. gpm			12 L/minute 3.2 U.S. gpm			21 L/minute 5.5 U.S. gpm		
TEMPERATURE C	QUANTITY L	US gal	ENERGY MJ	QUANTITY L	US gal	ENERGY MJ	QUANTITY L	US gal	ENERGY MJ
>70	269	71	75	250	66	70	210	55	59
>60	321	85	89	261	69	73	214	57	60
>50	385	102	103	294	78	79	262	69	70
>40	unlimited >49 C			328	87	84	293	77	75
>30				unlimited >31 C			332	88	84
							unlimited >24 C		

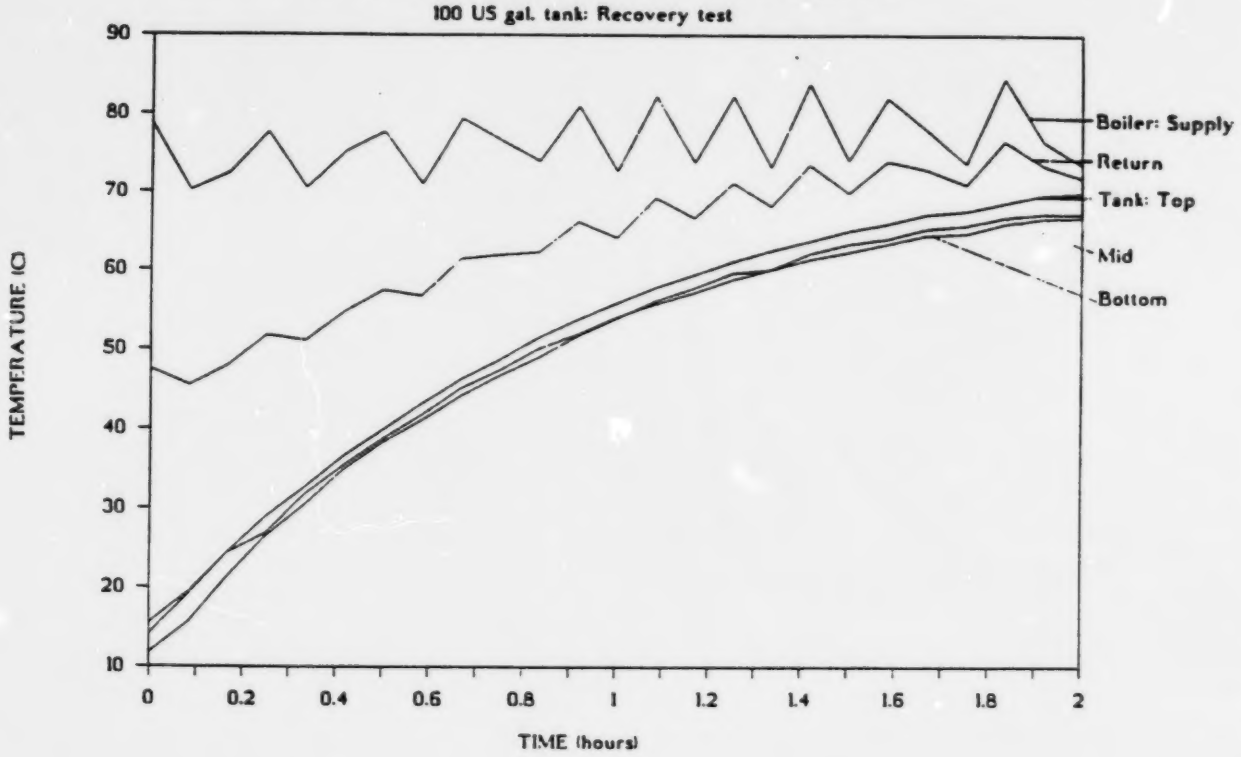
NOTE:

Boiler average supply temperature 80 C (176 F)
flow 11 L/min. (2.9 U.S. gpm)

STANDING HEAT LOSS:

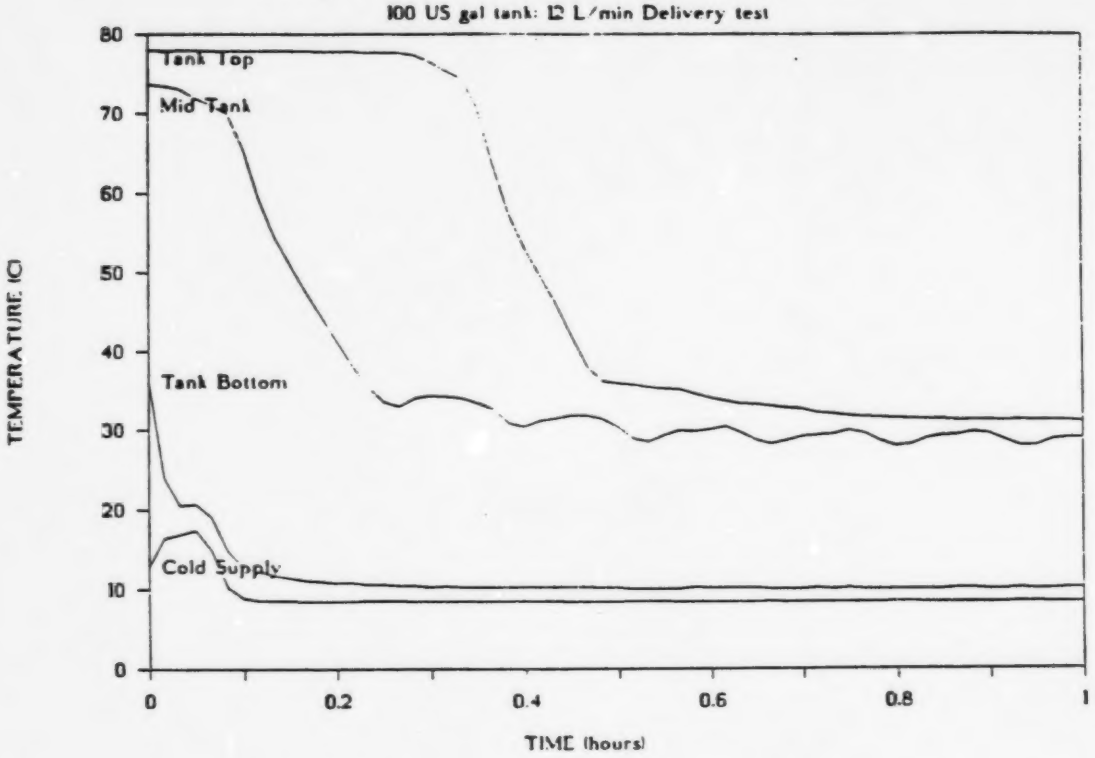
340 W (50 C temp. difference)
0.7 C/hour
1.4 %/hour (50 C temp. difference)

A & R METALS TEST FACILITY



A & R METALS TEST FACILITY

100 US gal tank: 12 L/min Delivery test



A & R METALS

120 U.S. gallon (454) L tank

RECOVERY:

Time to average tank temperature of -

50 C	1.08 hours
60 C	1.75 hours
70 C	2.33 hours

NOTE:
Boiler average supply temperature 80 C (176 F)
flow 11 L/min. (2.9 U.S. gpm)

DISCHARGE:

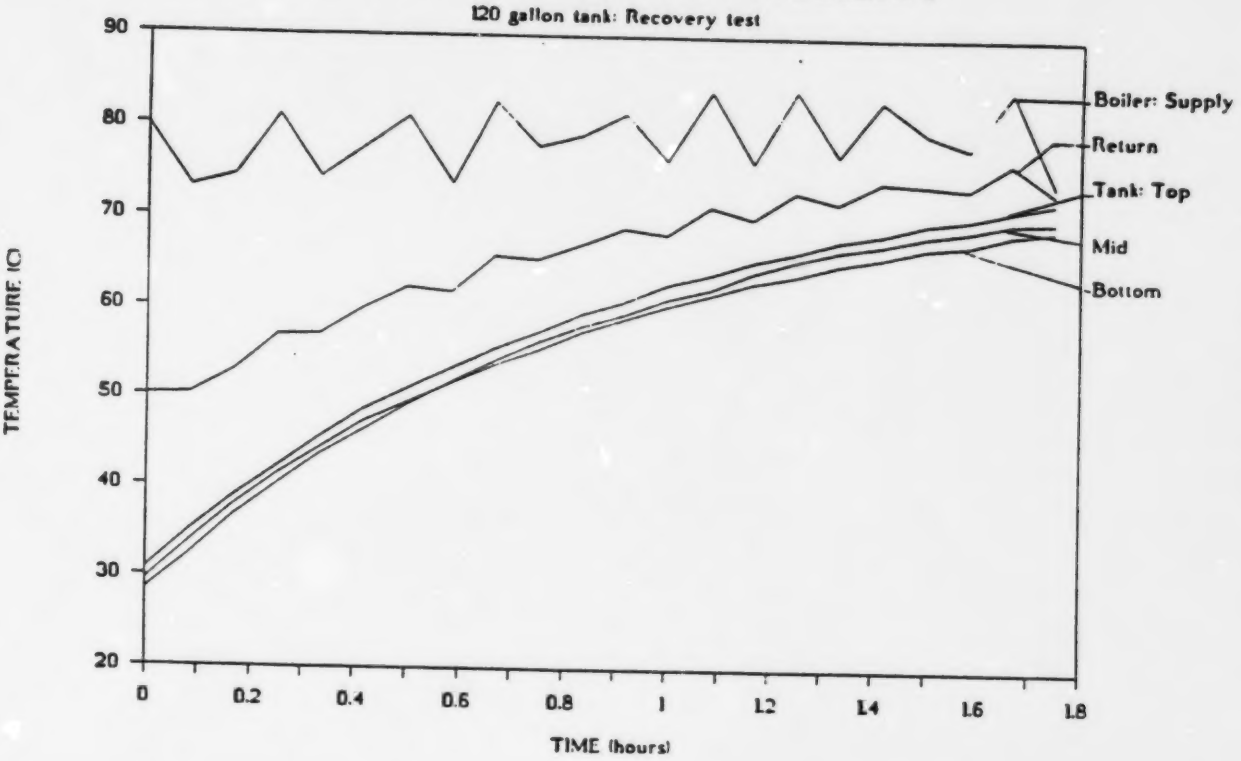
	7 L/minute 1.8 U.S. gpm			12 L/minute 3.1 U.S. gpm			21 L/minute 5.5 U.S. gpm		
TEMPERATURE C	QUANTITY L	QUANTITY US gal	ENERGY MJ	QUANTITY L	QUANTITY US gal	ENERGY MJ	QUANTITY L	QUANTITY US gal	ENERGY MJ
>70	321	85	92	293	77	83	233	62	68
>60	394	104	109	316	83	88	250	66	71
>50	unlimited >55 C			328	87	91	278	73	77
>40				374	99	98	322	85	84
>30				unlimited >33 C			367	97	89
							unlimited >26 C		

NOTE:
Boiler average supply temperature 80 C (176 F)
flow 11 L/min. (2.9 U.S. gpm)

STANDING HEAT LOSS:

375.0 W (50 C temp. difference)
0.6 C/hr
1.2 %/hr (50 C temp. difference)

A & R METALS TEST FACILITY



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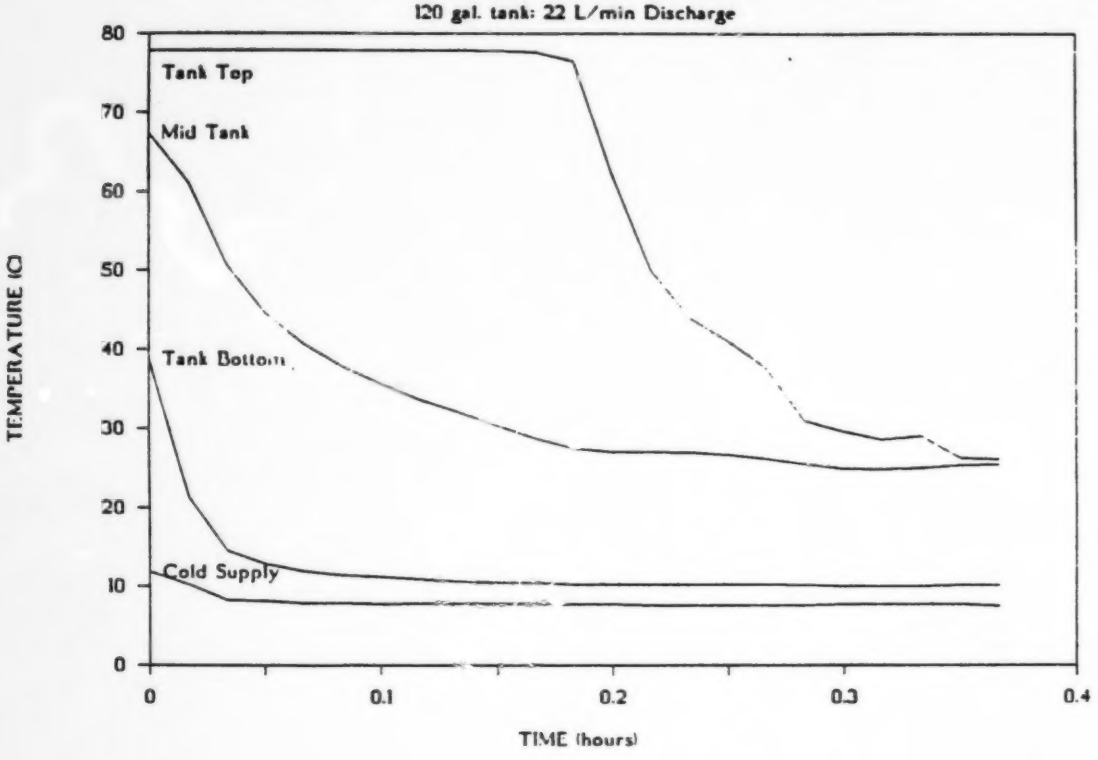
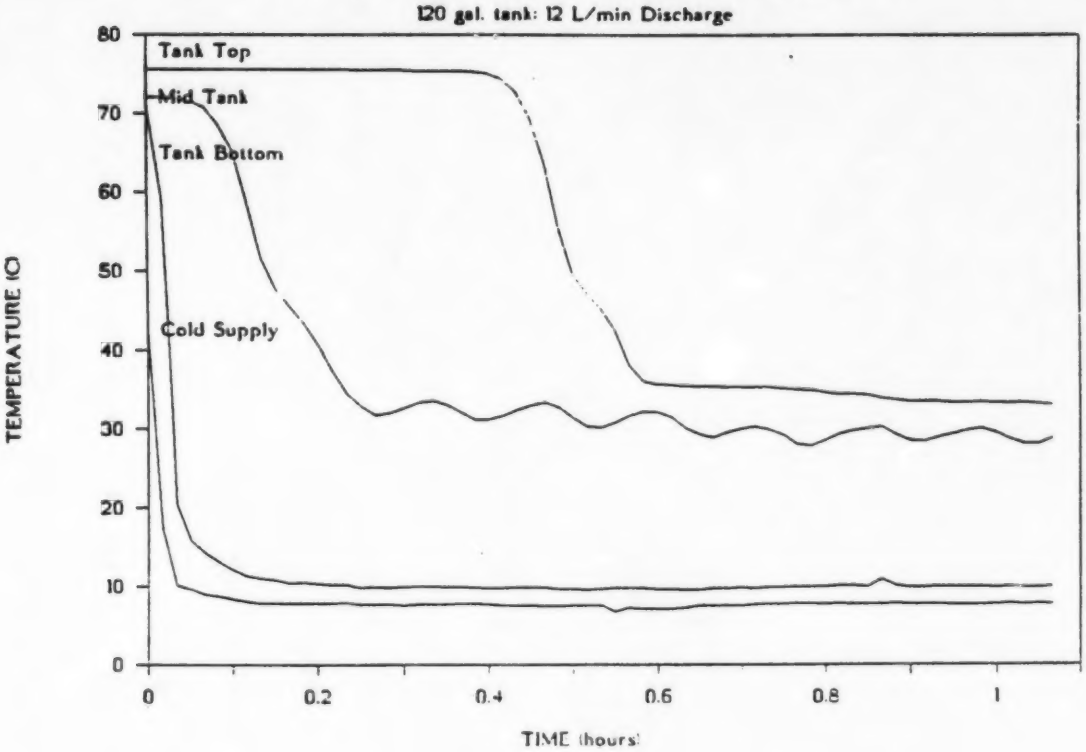
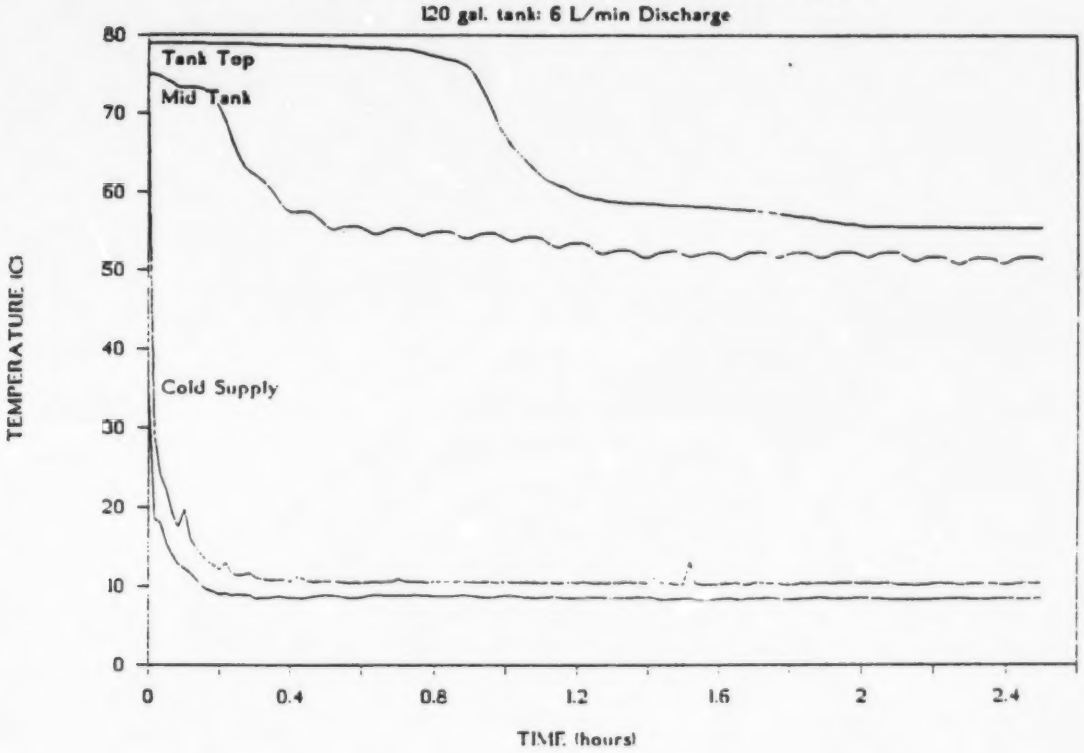


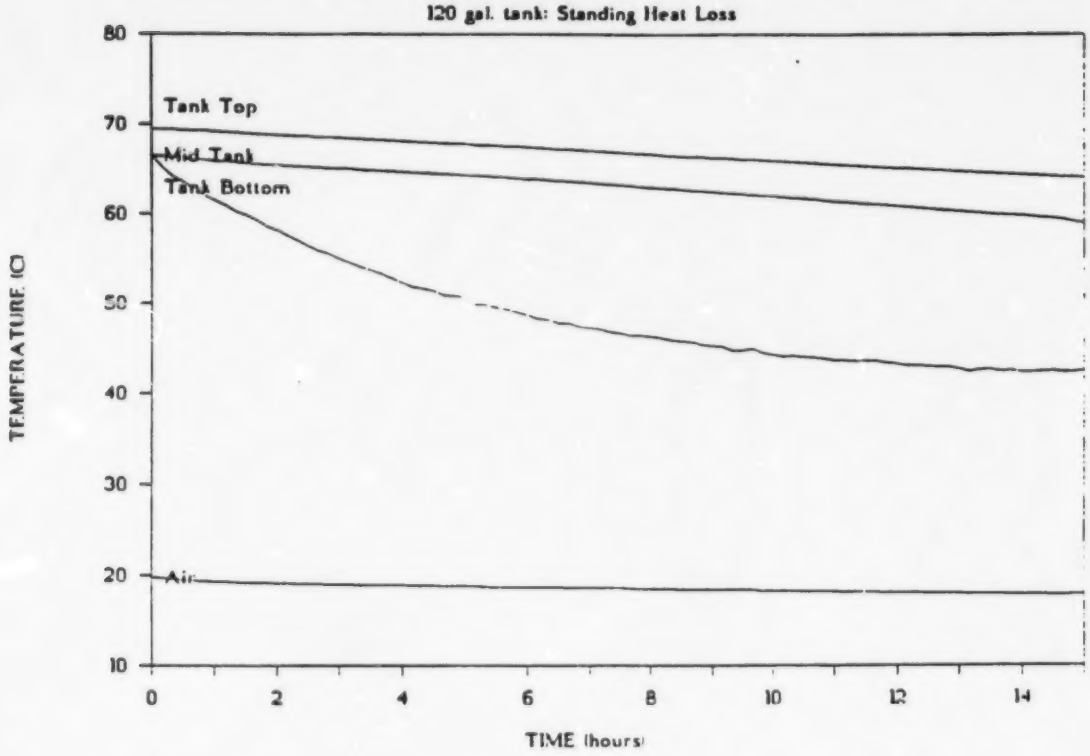
A & R METALS TEST FACILITY



A & R METALS TEST FACILITY



A & R METALS TEST FACILITY



APPENDIX G

DIVIDED COIL PERFORMANCE ESTIMATE
100 U.S. gallon tank
120 U.S. gallon tank

ESTIMATED PERFORMANCE WITH DIVIDED COIL HEAT EXCHANGER

50 C Temperature Rise:

TANK (L)	DEMAND (L) 10 min.	1 hour
379	262	816
454	295	894

90 F Temperature Rise:

TANK (U.S.gal.)	DEMAND (U.S. gal.) 10 min.	1 hour
100	69	216
120	78	236

Test at 21 L/min (5.5 U.S. gpm) demand flow
Boiler supply at 80 C (180 F) & flow of 22 L/min (5.8 U.S. gpm)

TANK (L)	CONTINUOUS FLOW RECOVERY (L/hour)
379	412
454	482

TANK (U.S.gal.)	CONTINUOUS FLOW RECOVERY (U.S. gal./hr)
100	109
120	127

Boiler supply at 80 C (180 F) & flow of 22 L/min (5.8 U.S. gpm)

Appendix H

Contract Directory Information

Title

Development of Corrosion Resistant storage tanks for Solar Heated Wate

Scientific Authority

Solar Engergy Development Program
Renewable Energy Branch
Energy Mines & Resources
580 Bootch Street
Ottawa, Ontario
K1A 0E4

Contractor

A & R Metal Industries Ltd.
12240 Vulcan Way
Richmond, B.C.
V6V 1J8

Contract #37SZ 23216-6-6277

Principal Investigator: M. Lookman, D. Lemon, K Cooper

Cost

1986	3050.60
1987	69.505.77
TOTAL	72.556.37

Duration: November 1986 to July 1987

Contractor Contribution: 27.56.37

45.000

Objective

To develop cost effective corrosion resistant Solar Water Storage Tanks.

Results

Recommendations were developed for the use of types of materials to utilize in building storage tanks. Consideration was given to different types of stainless steels, copper, bronze, fiberglass reinforced copper, tank and mild steel coated tanks. In addition tank design types of foams and types of jacketting and heat exchangers were analyzed. The overall result was to develop an effective tank for a cost of approximately $200.

Conclusions

Water qualities of a particular area should be analyzed in a given area in order to determine tank material. The credibility of the whole system depends upon this. In addition overall tank heat transfer and heat retention can be drastically inproved.